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VOLCANISM AND TECTONICS OF THE MOON

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16. Abstract The first section of this two-part book presents a map of lunar volcanic features based on methods of photogeology. Domes, central volcanoes, dikes, volcanic ridges, areal effusions, volcanic regions and craters of volcanic origin are widespread on the Moon. Volcanogenic craters can be recognized by their structure, distribution and nature of their walls. Different varieties of volcanogenic craters are classified and compared with meteorite craters. Distribution analysis shows that 33.5-50% of the lunar surface is composed of volcanogenic craters and areal effusion and volcanic regions. Differences between terrestrial and lunar volcanic craters are discussed and explained. The second section present a map of lunar mare basins and discusses the nature and time scale of their formation; the basins were formed side by side with their filling by mare material. Magma generation and routes for its dispersal are indicated. Evidence of endogenous history help explain the Moon's interior.			
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Annotation

The book deals with volcanism and tectonics of the Moon.

In the section by A. L. Sukharov, "Volcanic features on the Moon," there is a discussion of diagnostic indications of volcanic lunar features (central-type volcanoes, volcanogenic craters, areas of effusion, etc.), their morphology and extent are described, a comparison of lunar volcanic features with those on earth is made, as is a comparison of volcanogenic and meteorite craters of the Moon. The possible reasons for the difference between lunar and terrestrial volcanic structures are discussed. There is a map of the distribution of lunar volcanic features.

In the section by V. G. Trifonov, "The geology of the lunar mare basins," the tectonics of lunar mare are examined, as are their marginal cordilleras and peripheral belts, the length of development of these structures is substantiated, and regularities of their spatial distribution and possible conditions for their tectonic and magnetic formation are shown. The work contains a map showing the distribution of rock complexes of different ages on the Moon's surface.

Foreword

Recently, a large amount of new information on the geology of the Moon has been obtained through research by Soviet automatic stations and the work of American astronauts. Samples of lunar rock have been brought back to Earth and studied, their radiological age has been determined, and new information has appeared on the distribution of gravitational anomalies on the Moon. Many questions, which previously caused heated discussion, have now been solved conclusively.

There has been a wealth of new information, the most important of which is the possibility of direct study of lunar rocks which, as it were, has eclipsed the traditional method for studying the formation of its surface -- geological interpretation of photographs. At the same time, in this field we have recently obtained a colossal amount of material in the form of large-scale photographs of the Moon's surface taken by artificial satellites. These photographs, as it were, have brought the Moon's surface closer to us and allowed us to see many details on it, previously undiscernible in telescopic photographs. Undoubtedly, this research is extremely important, since it allows us to determine the general regularities of the surface formation of heavenly bodies and, by the same token, answer a series of questions of comparative planetology.

This investigation, in essence a continuation of the compiling of geological maps of the Moon's surface, was carried out at the Institute of Geology of the Academy of Sciences of the USSR.

Nowadays no one has any doubt that the surface of our natural satellite is extensively covered with volcanic rock and, consequently, volcanic relief forms must play a significant part in the structure of the Moon's surface. Hence, there was an attempt to show those relief forms on the Moon's surface whose structure could be linked with volcanic processes. Apart from the already-known craters and basins of lunar maria, positive relief forms, many of which are probably central volcanoes, are visible on large-scale photographs.

The first section of the book is devoted to the analysis of positive lunar relief forms and craters, classifying and allotting them to types, the volcanic origin of which is very probable. This section contains a map showing the attempt which was made to distinguish volcanic relief forms and evaluate their role in the structure of the lunar surface. The analysis conducted shows that volcanism played an important part in the formation of lunar relief, and this must be taken into account for any theories showing the development of this heavenly body.

The second section of the book analyzes the formation and history of development of lunar mare basins. It is known that

these extensive depressions on the Moon's surface have been the subject of discussion between supporters of both the meteoric and volcanic origin of its relief. Therefore, it was important to show the features of the formation and shaping of these structures. Facts which show the formation of these relief forms during a geologically long interval of time and the gradual formation of paragenetic structures are probably proof of their endogenous origin and volcanic and tectonic nature. A description of the structure of lunar mare basins is accompanied by a geological map of the Moon's surface, without which such analysis would have been impossible.

It is believed that further study of the geology of the Moon, on the one hand, will allow corrections to be made on a number of proposals put forward in the work and, on the other hand, will be made easier due to the structural analyses and typification of lunar relief forms.

Table of Contents

	Page
Foreword	111
VOLCANIC FEATURES ON THE MOON (A.L. Sukhanov)	1
Introduction	1
Meteorite Craters on Earth	8
Statistics of Lunar Craters	17
Volcanic Forms on the Lunar Surface	24
Domes	24
Central Volcanoes	47
Dikes and Volcanic Crests	58
Volcanic Regions	59
Volcanogenic Craters	61
Mare Formations	82
Types of Volcanogenic Craters of the Moon	88
Concentric Craters	88
Primitive Rings	99
Mature Craters	102
Petal-like Craters	104
Complex Cirques	107
Explosive Craters (Craterlets)	112
Impact Craters	115
Terrestrial Analogs of Lunar Features	133
Effusive and Pyroclastic Deposits	134
Cinder Cones and Pit Craters	141
Stratovolcanoes	142
Large Caldera and Ring Complexes	146
Extent of Volcanic Features on the Moon	158
The Age of Lunar Volcanism	160
Peculiarities of Lunar Volcanism	163
Dynamic Regime of Magmatic Foci	164
Differentiation and Outgassing	167
Scattering of Pyroclastic Material	170
Structure of the Crust	172
Some Peculiarities of Structures on Mars	176
Conclusions	180
References	185

	<u>Page</u>
THE GEOLOGY OF LUNAR MARE BASINS (V.G. Trifonov)	200
The Subject of Study, Terminology, Morphology and Systematics	200
The Multistage Nature of Formation Processes of Lunar Mare Basins	240
Circular Basins of the Mare Imbrium Type	240
Circular Basins of the Mare Nectaris Type	249
Circular Basins of the Korolev Thalassoid Type	254
Irregularly Shaped Maria	258
Multistage Development as a Reflection of the Long-Term One	261
Regularities in the Distribution of Circular Mare Basins and Mare Material on the Moon's Surface	265
Magmatism, Mascons and the Lunar Crust	268
Conclusions	275
References	279

VOLCANISM AND TECTONICS OF THE MOON

A. L. Sukhanov and V. G. Trifonov

VOLCANIC FEATURES ON THE MOON

(A. L. Sukhanov)

/7*

Introduction

The question of the origin of lunar craters arose as soon as it was possible to detect them through a telescope. In the middle of the seventeenth century, Robert Hook put forward two possible ways in which they could have been formed and even made a model of lunar processes: "endogenous" craters were made by boiling resin and "exogenous" by throwing pebbles into a soft target.

The theory of the meteoritic origin of lunar craters was the result of realizing that meteorites fall on Earth. This theory was first put forward at the beginning of the last century (Bibershteyn), developed in 1828 by Gruytuzen, and perfected and substantiated in a large amount of material by G. Gilbert (at the end of the last century). It was developed in its modern form by R. Baldwin, H. Urey, W. K. Hartmann, B. Yu. Levin, K. P. Stanyukovich and others.

Conjectures on lunar volcanism were put forward in the eighteenth century, for example, by V. Herschel. After information had been built up on terrestrial calderas, D. Dena put forward the hypothesis of the caldera origin of lunar craters. It was developed most fully at the end of the 1940's by A. V. Khabakov simultaneously with J. E. Spurr, and later completed by works by G. Fielder, G. Green, P. Moor, G. Kuiper and many others.

The essence of the meteoritic hypothesis is the following. Almost all lunar relief forms are made by meteorite and asteroid impacts. When a meteorite hits the lunar surface, its matter is instantaneously converted into a high-temperature compressed gas; during the explosion, a crater appears. Rock on its edges is lifted, split, or even overturned. This ejecta forms a wall, gradually becoming lower and disappearing as it moves away from the crater; part of the matter falls back into the crater, forming the compressed floor. Individual "streams" of ejecta spread beyond the wall, forming a ridged and furrowed flowing relief, and, even farther, there are dispersed ejecta which form radial systems. The rays of these systems form during the fall of

* Numbers in the margin indicate pagination in the foreign text.

of unscreened debris, forming secondary impact craters; in its turn, a strip of ejecta extends from each of these craters. Primary meteorite craters are formed during an explosion and are circular, regular, cup-shaped formations. Secondary impact craters are simple hollows; therefore, they are small, elongated and are grouped in strips, swarms, clusters and loops. It is thought that a strip of debris can fall simultaneously -- a ditch then forms when the hollows run together-- or each fragment falls over a certain interval of time-- rows of successively overlapping craterlets then occur. During impact, fissures form around craters; they can also occur along the chain of isolated secondary impact craters. /8

The central peaks of craters are, according to various authors: a) the result of rebounding of the crater floor, after compression, occurring while the shock wave is taking place (Baldwin, 1967); b) heaps of material ejected vertically which fall back into the center of the crater (Shoemaker, 1968); c) the result of isostatic adjustment of the impact hollow. The flat floors of the craters are usually believed to be the result of isostatic adjustment; some authors suggest that deep craters are mechanically unstable, their walls do not hold their own weight, and a viscous "leaking" of the crater floor begins, causing them to be leveled out (Quaide et al., 1965). Leveling by micrometeoritic bombardment is feasible for small craters (with a diameter of several kilometers) (Collins, Smith, 1967; Ross, 1968). Terraces on the inside slopes of craters occur when large slabs of material slip from the slopes. It is believed that, when a meteorite impacts and explodes, concentric waves similar to those in liquid can be caused; some of these "congeal" forming double craters, concentric structures, etc.

Large circular mare basins occur as the result of asteroid impacts (Baldwin, 1949; Shoemaker, 1968). Here, the asteroid is partly vaporized and partly split and hurled over great distances. Large blocks and masses of incoherent material fall on the edges of basins, forming marginal ring ranges -- cordilleras. Those blocks which fly over the cordilleras are carried for hundreds of kilometers; when they fall, they form grooves in the area up to several tens of kilometers long, directed radially towards the center of the impact basin. The incoherent material forms strips and streams, which are also radial to the center of the basin; apart from this, large secondary impact craters are formed which also sometimes form chains. The maria are filled with lava generated when the lunar crust fuses when asteroids explode or during subsequent heating-up of the substratum. The cooling of lava causes cracking of its surface, and elongated grooves are formed -- so-called rilles,-- as are warped folds in the form of long, low "mare ridges". Apart from radial systems of ejecta around maria, radiating cracks and concentric elevations and depressions are formed.

Supporters of the meteoritic hypothesis believe that it can explain the parameters of lunar craters (the relationships of depth, diameter and wall height) and their number (the increased number of craters with a reduction in their diameter, conforming to certain laws) and also the presence on the Moon of large craters, none of which are present on the Earth.

The meteoritic hypothesis is complemented by that of initiated volcanism, according to which, after a meteorite impact, volcanic activity can begin in a crater, this impact being the "trigger" which causes cracking of the cover of an already-existing magmatic focus by changing the P-T° conditions in the heated area below the crater, etc.

Until recently, the majority of selenologists supported the meteoritic hypothesis for explaining the lunar relief forms. When new material appeared (medium- and large-scale photographs of the Moon's surface) and new problems were studied (the selection of landing sites for spacecraft), more geologists were attracted to this work, and now the endogenous theory is receiving more recognition. /9

Supporters of the endogenous theory believe that a considerable part of lunar craters are volcanic forms, that is, analogs to volcanic craters, calderas and ring complexes on Earth. The number of these forms among all lunar craters is evaluated in different ways by different authors. According to this hypothesis, crater walls are formed by ring intrusions, ejecta from a central vent or debris from primary domes; the smooth floors are formed by volcanic covers and flows; the central peaks are volcanoes; ray systems form during catastrophic volcanic explosions and secondary craters during incidental eruptions. Indications of the volcanic origin of craters are believed to be: their link with cracks and chain arrangements, the polygonal nature of walls, and some feature of the internal structure and relationships. Recently, after large-scale surveying carried out by spacecraft, additional possibilities have occurred for distinguishing volcanic craters. Among them are: a smaller number of impact craterlets on the sloping parts of crater walls in comparison with their floors, which indicates that the surface of the wall is younger; the absence of stream deposits and secondary craterlets on the slopes of a wall; the covering of parts of the floor of the crater by material from its wall; lava domes, volcanic cones, subsided craters and craters with dark (ashy) aureoles.

Mare basins, according to this theory, are believed to be volcanic and tectonic depressions surrounded by tectonic ring ranges -- cordilleras with radiating crack systems and associated concentric basins, also of tectonic origin. Sometimes, there are young, dark mare in the depressions filled with old

effusions; the light color of the latter is caused by prolonged processing of their surface. On some sections of the mare surface, domes and cones similar to small volcanoes on Earth have been noted.

The meteoritic and volcanic hypotheses of the origin of the Moon's relief were developed simultaneously and in constant conflict, each new fact obtained during observations being used simultaneously to confirm one or the other hypothesis, since the limited nature of our knowledge of processes taking place on the Moon allowed for different, and sometimes completely contradictory, interpretations of the same observations. Supporters of both theories entered into controversies and tried to explain from one point of view the greatest possible number of features noted on the Moon, sometimes putting forward quite precarious interpretations. Several structures were examined in which the most clearly expressed indications of volcanic (or, on the other hand, meteoritic) origin were shown, and the conclusions made were openly or secretly extended to the majority of the remaining structures. The existence of craters of different origin was generally accepted, but the volcanologists left the examination of the features of meteorite craters to their opponents and vice versa; no overall mapping of volcanic or impact forms alone was done. As a result, when reading works of one point of view, one gets the impression that the overwhelming majority of features of the lunar surface owes its appearance to volcanism and tectonics, and in other works it follows that volcanism on the Moon, if it is evident, is however complementary and very weak. /10

According to the author, the meteoritic theory is an unsatisfactory explanation of the following features of the lunar surface: a) the central peaks and ranges of craters, domes, the flat floors of craters and concentric structures in them; b) the regularities of crater distribution and the structural interrelationships of some craters; c) irregularities in the distribution of the number of craters depending on their diameters; d) the extended belt of cracks, large dislocations along them, etc. Concepts of the impact origin of radial and concentric structures around the maria do not always agree with morphological analysis of the structures. With respect to craters with a diameter greater than several kilometers, the meteoritic theory must be based on assumptions and calculations, since there are no reliably indicated meteorite craters of this size on Earth.

However, neither can the volcanic theory explain all features of lunar relief. This is true of stream-like and ray systems, large secondary craterlets, the normally logarithmic distribution of the number of craters according to diameter (in the first approximation) and the uniform distribution of craters with a small diameter over an area. Comparison of lunar craters with calderas shows the significant difference between them, and there are no analogs on Earth for the largest cirques.

Over recent years, information has been accumulated on the significant scale of lunar volcanism; but, undoubtedly, meteorites of different sizes are constantly falling on the Moon, forming craters, but in the past, apparently, this process was more intensive; undoubtedly there are also traces of tectonic movements on the lunar surface. Large-scale photographs which recently appeared showed that lunar craters are characterized by a wide range of structural features, and these are very changeable in different craters. Obviously, this shows the heterogeneity of craters, the different conditions and dissimilar history of their formation. Highlands on the lunar surface have a different structure.

If it were possible to distinguish volcanic forms "in pure form" among these heterogeneous craters and highlands, this would allow certain conclusions on the nature of lunar volcanism to be made, allowing comparison with their process on Earth. Until recently it was very difficult to solve this problem in a general form, since existing selenographic material did not allow sufficiently detailed interpretation of the lunar surface to be made, and existing publications on the subject were limited to certain areas or specific examples from different regions of the moon (Moor, 1966b; Moor, Cattermole, 1967; Okulitch, 1966; O'Keefe et al., 1967; McCauley, 1968; McCall, 1968; Milton, 1968; Gors et al., 1970). Now, with the appearance of many photographs taken by spacecraft, one can attempt to solve this problem, even though in the first approximation.

This work will pursue the following basic aims:

1. the search for morphological indications inherent in positive and negative volcanic forms of the lunar surface;
2. distribution on the basis of indications of positive and negative forms which could be volcanic (with some degree of reliability);
3. an approximate division of volcanogenic craters on the Moon's surface into types; /11
4. comparison of isolated forms with terrestrial volcanogenic formations.

Telescopic photographs on a scale of approximately 1:1,500,000 (Kuiper et al., 1960) were used in the work, and photographs taken by spacecraft (Orbiter 1 - Orbiter 5, Zond 3, Zond 6 - Zond 8, Ranger 7 - Ranger 9) -- the scales of these photographs vary widely: from 1:300,000 to 1:5,000,000. Larger-scale photographs were rarely used, since they cover relative small areas, and small-photographs cannot always be geologically interpreted, owing to the insufficient image detail. Some telescopic photographs and

pictures taken by the Zond 3 form stereopairs, which, of course, increases their information value; but the main mass of photographs are single pictures (photographs taken by satellites in the Orbiter series also often overlap, but each one of them is made from individual strips, and it is impossible to obtain a stereographic image for the whole photograph).

When studying these photographs, the author first of all turned his attention to structures, whose volcanogenic origin was most obvious, that is, those formations which, according to morphology, position and relationship with the surrounding structures, could not be meteoritic ones, even if some strained interpretation is allowed for. After this, a systematic search was made for structures with characteristics similar to those which were separated at the first stage. Sometimes, such "second generation" structures had all the signs of being volcanogenic, but normally only one or two signs were necessary to fix them accurately, and the rest had none or they were very poorly expressed. If indications of endogenous origin were so poorly expressed that the structure could also be meteoritic formation, this structure was only assumed to be volcanogenic. If the structure was characterized by some indication clearly showing its meteoritic origin, it was considered as primary and meteoritic, although often similar forms are complicated by volcanogenic new formations. Of course, a map compiled in this way is somewhat subjective; however, it is still not possible to determine the measure of this subjectivity. It must be noted that if one and the same area is covered by small- and large-scale surveying, a larger number of volcanogenic forms can be interpreted on large-scale photographs; this gives reason to hope that on the number of volcanic structures on the compiled map will be underestimated rather than overestimated.

Geologic and morphological maps of the Moon, compiled earlier by M. S. Markov, V. G. Trifonov, P. V. Florenskiy and the author (the collection "Problems of lunar geology," 1969), are compiled according to the age principle. Here, the main attention was focused on the stratigraphic arrangement of lunar formations, irrespective of their origin.

The map shown in this work was compiled by the author during 1969-1971. It is compiled on the genetic principle. Forms of different age but similar morphologically (and, apparently, genetically) are shown by one symbol. Complete mapping was not done, since only volcanogenic forms were isolated, and all formations of impact and unknown origin were not shown. -- white spots were left. Here, some of the contours coincide with contours on maps contained in the collection "Problems of lunar geology" (1969); however, whereas on these maps the marking of a contour shows the age of a formation irrespective of origin, on the map in this work the marking of a contour means the origin of the structure,

/12

and the age is not examined. Developing the method for determining the age of volcanogenic formations will only become possible after solving the problem of which lunar forms should be considered volcanogenic.

Most of the forms isolated (approximately 2/3) cannot be considered reliably volcanogenic, although, according to information now available, the probability of their endogenous nature is greater than their meteoritic one. On the map, these forms are shown as being presumably volcanic. But even if part of the impact or purely tectonic formations were included in this group, analysis of all the isolated forms -- both reliable and conjectural -- would allow one, having such a large amount of statistical material, to show the general regularities of their formation, typical of the majority of these forms and for individual subgroups, for example, to establish the "depth-diameter" relation for different types of craters (Katterfel'd, 1965).

The following remarks must also be made.

First of all, this map does not claim to be a complete and accurate reflection of all volcanogenic structures on the Moon's surface: Successive study of photographs at the author's disposal has meant fixing the information accumulated relative to the distribution and interrelation of volcanogenic relief details. The most pictorial and convenient form of fixing was applying these details to a topographic base. However, the results of this work should not be considered final for the following reasons.

1. The arrangement of objects on the far side and limb of the Moon differs somewhat on the topographic base compiled at the GAISH [State Astronomical Institute im. P.K. Shternberg] ("A complete map of the moon," 1969) and at NASA ("Lunar farside chart," 1968). Here, the GAISH topographic base was used; however, it is possible that in the future the position of objects will be made more precise.

2. The arrangement and details of objects on topographic maps is somewhat diagrammatic in comparison with what is visible in photographs. This makes it difficult when drawing the geological boundaries.

3. Photographic material used in compiling the map varied in quality. This is also true of telescopic photographs (differences in the detailed nature of the image for the center of the disk and the limb) and of photographs from spacecraft (differences in the angles of photography, the height of the sun and the scale; the deterioration of many photographs during micro-filming). Often, geological interpretation of them was made more difficult or even impossible (although they were suitable for compiling a generalized topographic base). If there are additional

photographs taken with telephoto lenses for a section of a small-scale photograph, one can see on them many more objects of interest to us than on a section taken on a small scale. This gives reason to suppose that areas covered by small-scale photography are in essence "geologically white spots," although some objects on them are still visible. In this way, the absence or sparsity of volcanic forms on any part of the map still does not mean that there are none in that particular area.

4. Finally, the compilation of a complete and accurate map of all volcanogenic structures is a task which can only be solved by the efforts of a large collective over several years. The map shown here is only one of the first attempts in this field, and is therefore diagrammatic.

The detailed character of the forms isolated is given in sections "Volcanic features on the lunar surface" and "Types of volcanogenic craters of the Moon." In essence, the sections are detailed explanatory notes to the basic map. /13

But, before examining lunar volcanic forms, one must determine which of the structures inherent in lunar craters are seen in meteorite craters on Earth and, consequently, can be interpreted as impact formations. We must also dwell on the question of the statistics of lunar craters, since many people believe (Baldwin, 1967) that the results of these statistics will finally prove the meteoritic origin of all craters on the Moon.

Meteorite Craters on Earth

In a catalogue of structures for which the meteoritic origin is proved or assumed, there are 115 formations ("A catalogue of impact structures," 1968). The dimensions of these forms are from tens of meters to several tens of kilometers. Among them, the most interesting are structures with central peaks, ring elevations and depressions; there are 19 of these. Recently, one more formation of this type was described -- Gosses Bluff (Crook, Cook, 1966); the Puchezh-Katun' dislocations are thought to be of meteoritic origin.

The existence on Earth of one proven impact crater with a central peak would allow one to affirm that some lunar craters with a central elevation also occurred as the result of meteorite explosions. By the same token, the central peak in a lunar crater, by itself, does not show that it is volcanogenic. The same can be said of the concentric structures of craters.

However, no meteoritic matter has yet been found in any of the 21 craters on Earth complicated by central peaks and concentric structures. A crater such as this would be listed as

presumably meteoritic if "diagnostic evidence of impact origin" was found in it, namely:

- a) gravitational and magnetic anomalies;
- b) breccias;
- c) fused and vitrified rock;
- d) parallel crack networks in minerals, isotropy of quartz, plagioclase, etc;
- e) shatter cones in breccias and surrounding rocks;
- f) the presence of high-barometric pressure modification of silica (coesite and stiboverite).

Consequently, the question is how reliable are these indications.

Apparently, geophysical anomalies can indicate the presence of a buried structure of a certain form, but cannot be "diagnostic indications of impact origin."

Breccias, which also occur during volcanic, tectonic, exogenous and even intrusive processes (Ivankin, 1966; Bryant, 1968), can only indicate a meteorite crater when it is not possible to show their formation by any of the "terrestrial" methods. Otherwise, breccia will not prove, but only "witness on behalf of" the impact origin of a crater. /14

The fusion and vitrification of rock, apparently linked with volcanic process, ought to differ from fusion during meteoritic impacts. However, up until now the different criteria of these glasses has been insufficiently developed. Furthermore, the meteoritic origin of glass in craters on Earth is very problematic (Bucher, 1965; Currie, 1965); even for the most reliably substantiated meteorite crater, Brent, it was shown that the lens of nonshattered dacites in breccia are younger than the crater itself by the K-Ar method, that is, they are probably intrusive (Shafiqullah et al., 1968).

Undoubtedly, the parallel crack networks in minerals shows the significant stress in rocks; but, as far as the literature is concerned, the exact differences between impact and tectonic crack networks have not been established. Apart from this, these differences are "easily noticed during comparison" (Short, 1968). Among microdeformation of this type there are also descriptions of crack networks of structures, the meteoritic origin of which must be proved, for example, Clearwater, or of structures of a determined exogenous origin, for example, Carswell (Currie, 1969).

According to N. M. Short (1968), isotropy is the transition stage to the complete fusion of rock; in this case, this phenomenon can be observed in metamorphic tektonites.

Shatter cones and coesite are believed to be the most reliable indications of an impact (Dietz, 1968; Zotkin, 1969); for many craters they are the only proof of the structure's meteoritic origin. Shatter cones are noted in 12 of the 21 structures shown above, coesite in six.

The cones are conical, small-crack systems with a diameter of from several centimeters to several meters; sometimes there is an indentation on the top of the cone. As opposed to "cone-in-cone," these cones are developed in all rocks, both sedimentary and igneous. Small shatter cones can be obtained experimentally when high-velocity shells strike a target. But, as in the case of parallel crack networks, there is no proof that these cones cannot be formed during normal tectonic stress.

W. E. Elston and P. W. Lambert (1965) described such forms around a felsite neck. The cones were found in intrusive rocks; their tops were pointed toward the neck or in the opposite direction; there are sometimes parasitic cones along the basic cone.

G. C. Amstutz, (1965, a, b) made a petrographic study of cones from the Cripple Creek and Decaturville cryptovolcanic structures. He came to the conclusion that in Crooked Creek the growth of cones was slower and was linked with the increase of minerals parallel to the cone walls; hollows on the crown were caused by leaching (the Rayke effect). He explained the origin of similar cones at Decaturville by tectonic stresses affecting the orientation of the cones.

When studying and comparing the geological map of the Carswell structure, K. L. Currie (1969) had no doubt as to the endogenous nature of this formation with a prolonged and complex development history. There are also shatter cones in the rock of this structure.

Finally, there are cones in the lopolith area of Sudbury, the endogenous nature and prolonged development of which have been quite reliably established. /15

In this way, forms called "shatter cones" do not belong exclusively to meteorite craters and therefore cannot be a sufficient criterion for the impact origin of the structure. Furthermore, there are none of these cones in many well-studied craters, the impact origin of which has been proved or is almost certain; until now, they have not been found in lunar samples.

Coesite is found in some craters, but is not seen in volcanic structures (incidentally, apparently no systematic search has been done). The stability range of coesite is higher than a straight line with coordinates $p = 14.5$ kbar, $t = 300^\circ$ and $p = 31.5$ kbar, $t = 900^\circ$ (Khitarov, 1957). Some researchers believe that these conditions cannot be attained in the Earth's crust, and, consequently, coesite could only be produced during a meteoritic explosion.

However, even more pressure is required for the formation of diamonds than is necessary for coesite (by approximately 10 kbar); they are as metastable and, nevertheless, diamonds are brought to the surface (Sobolev, 1960); some authors even believe that diamonds are formed at a relatively shallow depth in the Earth's crust (Vasil'yev et al., 1968).

Conditions for the transformation of quartz into coesite (22 kbar) are created in tectonically disturbed zones (Khitarov, 1957; Short, 1968). Finally, there is information that there is coesite in the Richat basin, which was recently recognized as being endogenous by R. S. Dietz, who is the main adherent to the meteoritic idea (Dietz et al., 1969).

Therefore, we have no conclusive criterion for classifying craters as exogenous or endogenous forms. Twenty-one structures of complex form must be examined with respect to all these indications. Table 1 contains a list of these formations (in order of dimension growth), their diameters, structures and diagnostic indicators.

Possible Meteoritic Formations

Katland (No. 9). Contains coesite and large (up to 48 m) conoidal cracking in rock. However, 95% of the cones are oriented perpendicular to the stratifications in the limestone and sandstone which are developed here (Baldwin, 1968), and this allows one to assume that they are of nonimpact origin.

Serpent Mound (No. 10). A mineral was detected in dislocation cones, the composition of which could have been coesite. But the structure consists of "irregular angular fault blocks" (Baldwin, 1968), which is quite uncharacteristic of proven meteorite craters.

Bosumtwi (No. 12). There is coesite, but the internal part of the crater is under a lake and its structure is unknown.

Gosses Bluff (No. 13). There were concentric outcrops of dense rock on the surface, with circular crowns approaching a triangle. The elevation is approximately 6 km across. It is surrounded by a poorly defined 16-km basin. There are breccias

TABLE 1. COMPLEX STRUCTURES WITH INDICATIONS OF
METEORITIC ORIGIN

No. in se- quence	Name of structure	Diam- eter (km)	Structural features	Diagnos- tic indi- cations
1	Howell* (USA)	2.5	CE	b
2	Steinheim (FRG)	2.5	CE, rd, RE	b, c
3	Flynn Creek** (USA)	3.3	CE, rd	b, c, cs
4	Jeptha Knob** (USA)	3.5	CE, rd	b
5	Glasford** (USA)	4.0	CE	b
6	Crooked Creek (USA)	5.0	CE, rd, RE	b, c
7.	Sierra Madre (USA)	5.0	CE	b, c
8	Decaturville (USA)	5.9	CE, rd, RE	b, c
9	Kentland* (USA)	6.0	CE	b, c, C
10	Serpent Mound (USA)	6.3	CE, rd, RE	b, C?
11	Wells Creek (USA)	10.0	CE, 2rd, 2RE	b, c
12	Bosumtwi* (Ghana)	10.4	RE, rd	b, c, C
13	Gosses Bluff* (Australia)	16.0	CE, rd	b, c, g, cs
14	East Clearwater (Canada)	20.0	CE, rd	b, g
15	West Clearwater (Canada)	32.0	CE, rd, RE	b, c?, g, C
16	Carswell (Canada)	33.00	CE, rd	b, c, cs
17	Vredefort (SAR)	40.0	CE, rd, RE	b, c, g, cs
18	Richat (Mauritania)	50.0	CE	b, c
19	Riss* (FRG)	61.0	3RE, 2rd	b, g, cs, C
20	Manicougan (Canada)	65.0	CE, rd	b, g, cs
21	Puchezh-Katun'* (USSR)	100x60	CE, rd	b

* Structures for which the meteoritic origin is as possible as the endogenous one.

** Forms, the origin of which is not clear owing to insufficient information.

For the remaining formations, according to the author, endogenous origin is more probable.

Notes: RE -- ring elevations; rd -- ring depressions (2, 3 -- double and triple rings); CE -- central elevations;
C -- coesite; c -- shatter cones; b -- breccias;
g -- glass; cs -- crack systems in minerals.

on the ring crest and in the basin; there are pyroclastic breccias south of the dome. In the center of the dome a 1400-m vent does not protrude from the brecciated sandstones, shales and limestones; it is thought that there are saline layers at the bottoms of the

cut. The opinion of the meteoritic nature of this formation is based on the presence of dislocation cones and breccias, and is confirmed by the fact that there is no intrusive or diapir below the central elevation. The structure is quite complex, and in a description of it there are many features indicating endogenous origin (Cook, 1968; Crook, Cook, 1966). Hence, breccia of a central elevation coincide in time with specific layers and can be interpreted as interformational or detachment breccia. In a breccia cover around the elevation, there are also other rocks and signs of stratification; it is possible that this is an exogenous formation. In remelted breccias on Mount Pyroclast there is montmorillonite and pumice, and a fluidal nature is visible; outcrops of this rocks cut across the extent of this section. All this indicates the volcanic nature of the breccias described. The whole structure is on the intersection of a large anticline and a fissure zone; there is another dome with dislocation cones related to the same zone (Blinman); there is a reduction of depth in the core of Gosses Bluff. As for the absence of an intrusive or diapir core, a 1400-m hole did not show it: there are significant dome-like bends at distances of 1.5-2-3 km above the cover of the diapirs; it is possible there is a general swelling in the thickness of argillaceous rocks due to local rehydration (Kosygin, 1950, 1969). /16

Riss (No. 19). Here, there is not only coesite, but stiboverite synthesized at much greater pressures. However, these minerals are found in suevite -- a vitreous rock, which, according to W. H. Bucher (1965) was intruded into changeless breccia and flowed to the surface, giving typical volcanic bombs. It indicates that Riss, together with the Urakh volcanic field and the Steinheim basin of the same age, form a single northeast zone, which can be traced in the structure's base by geophysical information. /17

H. Williams (1941) stresses that limestone blocks around the Riss basin have traces of slippage on lower planes, whereas there are no secondary craters. He admits that these blocks were displaced when the central dome lifted, the subsidence of the top of which formed the Riss basin.

Howell (No. 1), Flynn Creek (No. 3), Jeptha Knob (No. 4) and Glasford (No. 5). These are small brecciated elevations, the origin of which is difficult to determine due to the lack of information in the literature.

The Puchezh-Katun' dislocations (No. 21). Described in detail (Firsov, 1965), but no satisfactory geological model for their formation has been suggested; the theory of their meteoritic origin remains valid.

One is drawn to the fact that the depth of the two largest structures mentioned, the Riss basin and the Puchezh-Katun'

dislocations, is one order less than required for an explosive origin: several hundreds of meters in comparison with several kilometers (Baldwin, 1965; Steinberg, 1969). The small structures -- Howell, Jeptha Knob, Flynn Creek and Glasford -- are completely dissimilar to the Brent meteorite crater (3.5 km), which is a crater without a central elevation.

Endogenous Structures

Steinheim (No. 2). There are brecciated limestones with shatter cones in this basin, which is 80 m deep and has a 40-m central elevation. Previously believed to be a typical example of cryptovolcanic structures, this basin is now believed by some researchers to be a meteorite crater.

W. H. Bucher (1965) showed that Steinheim and the volcanic region of the Urakh lie on a groove axis in the bottom, forming two caldron-shaped depressions in the groove. A field of hot springs stretches between the two formations. The hot springs also emerge on the rims of the Steinheim basin and in its central elevation, Klosterberg (Baldwin, 1968). Ring and radial faults are also well developed. This mainly indicates the endogenous origin of the structure.

Crooked Creek (No. 6). A polygonal basin with a central elevation and raised rims. According to G. C. Amstutz (1965a, b), the structure is situated on a chain of diatreme and dike fields and endogenous domes, on the intersection of this chain and the fissure zone. The polygonal outline is caused by direct fault cuts. As was said earlier, cones seen in Crooked Creek are linked with mineral growth and redissolving in the rock and not with impact or tectonic stresses.

Sierra Madre (No. 7). The dome, 5 km along the surface and 12 km in depth, contains limestone and dolomite breccias with cones. But a profile, compiled by several bores (Wilshire, Howard, 1968; Howard, Offield, 1968), shows that the thickness of the rock more than doubles toward the center of the dome. This rules out the possibility of meteoritic interpretation.

Decaturville (No. 8). This structure which R. S. Dietz (1968) thought meteoritic since there were breccias in the dislocation cones has the following features. Interformational breccias are of volcanic origin (Amstutz, 1965b) and are impregnated with pyrite, galenite and sphalerite. Cracks, developed in the dome and on its periphery, are of at least two different age generations. The dislocation cones are of tectonic origin and are linked with the formation of a vein of pegmatite. Decaturville is in the same chain as Crooked Creek.

Wells Creek (No. 11). A system of several concentric synclines and anticlines, thought to be meteoritic mainly because there are many dislocation cones in the upper (30 m) section of the cut and are reduced with depth. Since this argument is used for other craters and domes, it can be noted that the increase of pressure with depth causes conditions under which stresses will be solved in a different way from those on the surface.

Concentric bends in Wells Creek are limited to direct faults. The rocks on the rims of the basin fall away from the center, suggesting an explosion, but in the northern sector they fall to the center. At a distance of 13 km to the north, three more basins lie on one line, one of which, with a diameter of 600 m, has a central peak (whereas there are no peaks in much larger meteorite craters). Finally, there is igneous rock, embedded in breccia (Baldwin, 1968).

Clearwater (No. 14, No. 15). The structure consists of two adjoining lakes. In the eastern lake (diameter 20 km), the central elevation was revealed by drilling. To a depth of 1 km, the elevation is formed of deformed, hydrothermally altered gneisses, alternating with gabbro and diorite; in the upper section, there are veins of glass with fragments of shifting rock (the hole was not in the center of the elevation). There is breccia in the ring depression around the elevation which, according to M. R. Dens (1968), is impact, and, according to K. L. Currie (1965), is volcanic. By taking into account the fact that there are horizontal interlayers of marbles and conglomerates in these breccia and that the fragments in the honeycombed glass of the upper layers are small (up to 30 cm) and the lower part (below the conglomerates) is formed from massive dacite with streaks of serpentinite, breccia in East Clearwater have a clearly volcanic origin.

In West Clearwater (diameter 32 km), a 16-km ring of islands is formed in the water. The islands consists of deformed gneisses and diabasic dikes; to a depth of 400 m, veins and tubes of vitreous breccia can be seen with traces of a flow, which can be linked with montmorillonite (characteristic of volcanic glasses). There are Ordovician rocks on the gneisses, overlapped by breccia, but, which is most important, there are no Ordovician rocks in breccia fragments. Above, there is redeposited breccia with fragments of the former and, even higher, massive dacite, similar to dacites in East Clearwater; rocks with a dacite cover have been subjected to pyrometamorphism. K. L. Currie remarks that dacites differ from the gneisses of the base in composition and according to rare elements and could not have been produced when they were remelted, as was suggested in the meteoritic hypothesis.

There is also a change of direction in the gneiss-like nature of rock below Clearwater and a coincidence of direction of the

long structure axis with the orientation of a swarm of dikes to the north of this place.

Even if one assumes that magmatism was initiated, one must allow for the existence of diabasic and dacite foci at a depth of 7-14 km -- this is the brecciation and facility depth for a crater of this diameter (Ronka, 1968). Although coesite was found at Clearwater (Zotkin, 1969), this should be seen not as evidence of an impact, but as the sign of an endogenous origin of coesite, as in the Richat structure.

Carswell (No. 16). This dome-shaped elevation, surrounded by a narrow ring syncline and crest, was studied in detail by K. L. Currie (1969), who established the prolonged development of the structure, which did not agree with the theory of meteoritic origin. The protrusion of the gneissic dome lifted the arch of the rock to a greater height than that of the ring crest; it was accompanied by brecciation and the formation of dislocation cones and fault systems, which in this case are of a purely tectonic nature.

Vredefort (No. 17). This formation belongs to the same type as Carswell, but there is more deformation here and the erosion truncation is greater. A large granite dome, which tore through the sedimentary rock, is surrounded by a ring of lifted and shattered rock. The dome is almost in the center of the Witwatersrand structure and is close to the Buschveld lopolith; together with it and the Thompson ultrabasic intrusion, it forms a structural prolongation of the great dike (Bucher, 1965); the Vredefort axis of symmetry also passes in this direction. The use of the meteoritic hypothesis for explaining the origin of the dome is completely superfluous, especially if geological information is interpreted in the following way: "Isostasy should determine the final structure of the Vredefort ring. Tough basic rock thrust the granite upward hydrostatically" (Dietz, 1968, p. 172). /19

Richat (No. 18). As has already been said, in spite of the presence of coesite, field research has established that the structure is a destroyed endogenous dome (Dietz et al., 1969).

Manicougan (No. 20). An arched elevation of anorthositic gneisses surrounded by a narrow ring trench with a settling amplitude of up to 1 km; in the center of the arch there is an additional dome, 7-15 km across; the elevation is overlapped by lava breccias, similar to volcanic rock at Clearwater (Currie, 1965).

Hence, it can be established that there are no proven complex form meteorite craters on Earth. In these structures, whose meteoritic origin, if not proved, is completely likely, either the central peak is unknown or the degree of its morphological expression in the primary crater

cannot be explained or, finally, its vertical dimensions are very small in comparison with the crater (Puchezh-Katun' dislocations); the same applies to concentric structures around the crater. The central crests in terrestrial meteorite craters are not known; neither are terraces on the internal slopes, volcanic filling of the floors, nor the subsidence of the abutting closures of two neighboring craters. The initial relief of large meteorite forms on Earth has not been preserved, and conclusions on their reliefs are based on extrapolation from craters with small diameters. Therefore, it is insufficient to use analogs on Earth for solving the problem of the structure of meteorite craters.

Statistics of Lunar Craters

Graphs showing the distribution of the number of craters on a unit of area depending on their diameter (crater density) can be used for confirming the meteoritic hypothesis of the origin of lunar craters. The basic material for this is shown in works by W. K. Hartmann (1967 b-d, 1968). He and other authors believe that the values they obtained can be set on straight lines on a graph with a logarithmic scale (1-1 in Fig. 1) for the whole range of visible forms (with the exception of secondary craters), and the inclination of these lines is close to the slope of the curves reflecting the distribution of meteoritic bodies according to mass. Hence, it can be concluded that the general mass of lunar craters has a meteoritic origin and that the density of craters reflects the relative age of individual sections of the lunar surface.

On the other hand, morphological analysis shows that some of these craters have a volcanic origin; this should distort the size distribution graphs of craters (2-2 on Fig. 1). Therefore, the author has attempted to systematize and compare available data in the literature on the distribution of meteorites, meteorite craters and lunar craters according to size.

In order to compile an overall graph for the distribution of craters on the lunar surface (Fig. 2), works of the following authors were used: W. K. Hartmann (1967 b-d, 1968), W. K. Hartmann and F. G. Yale (1968), E. H. Walker (1967), J. E. Guest and J. B. Murray (1969). The main task was to determine irregularities in the distribution and all deviations in the number of craters -- excess and deficiency -- reflected on curves, as opposed to the method used by W. K. Hartmann and others, who compiled averaged rectilinear graphs. The divergence of information was quite large; the maximum values for the given interval could be five times greater than the minimum ones; however, sometimes not only the mean, but also the extreme values deviate from the rectilinear graph. The reliability of these deviations is confirmed by the fact that they are fixed for one and the same

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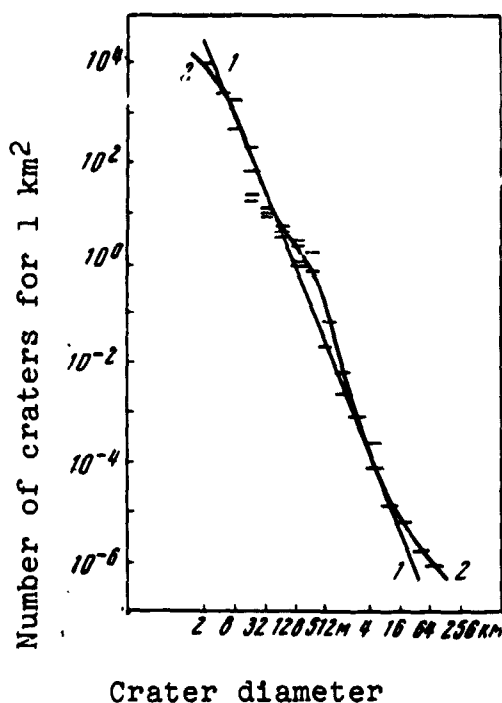


Fig. 1. Two possible interpretations for the calculations of crater density. The graph shows information on the distribution of craters according to diameter (the material is from Ranger 7 and telescopic observation). 1-1. A straight line, reflecting the general distribution tendency; 2-2. a curve, reflecting deviation from the normal logarithmic distribution.

entering a vicious circle.

Converting the value of a meteorite flux to the density of impact craters on the Moon's surface is also linked with irregularities when evaluating the size of craters formed and, correspondingly, the number of them. To say nothing of the fact that there is a significant variance of speeds for meteoric bodies and that their selenocentric speed is less than their geocentric one, and the dispersion of lunar fragments is made easier due to the smaller force of gravity, leaving aside all these complicating factors, we meet two basic problems.

diameter intervals for different curves, that is, various regions of the Moon. As a result, interesting regularities were shown which will be analyzed after estimating the value of a meteorite flux of the number of meteorite craters.

Different estimations of the value of a meteorite flux were converted to a single scale and drawn on the overall graph (Fig. 3) (in the conversion to the number of falls over 1 km² of the Moon during 3 billion years, using the modern density shower).

Data by the following authors were used: G. S. Hawkins (1963, 1964), L. F. Firsov (1965), R. G. Neswald (1966), J. F. Vedder (1966), T. N. Nazarova (1966), T. Grjebine (1967), G. K. Wall (1968), P. W. Hodge (1969), and L. M. Shkerin (1970). The overall graph shows that the estimation of the value of a meteorite flux by various authors varies by a factor of 1 or 2. Possibly, many of these estimates are understated owing to the lack of information; therefore, it is advisable to take the curve, the values of which are somewhat greater than the mean ones, as a base in the future.

Here, for masses from 10^6 to 10^{15} g (between asteroids and instrumentally observed meteors) of material is insufficient and cannot be used for lunar craters, without

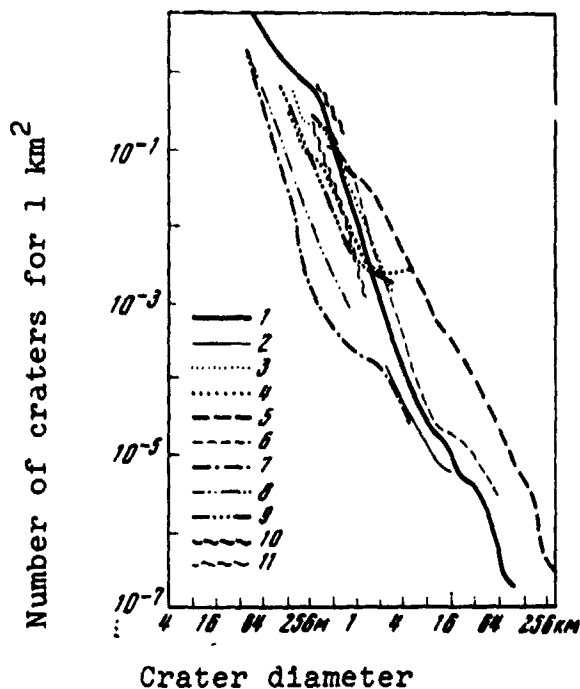


Fig. 2. The density of craters on various sections of the Moon's surface (average curves): 1. mean throughout all maria; 2. Mare Claritas; 3. the floor of the Alphonsus crater; 4. walls and central crest of Alphonsus; 5. mean throughout the highlands; 6. highlands near Mare Orientale; 7. Tycho; 8. Aristarchus; 9. Copernicus; 10. the central platform of Tsiolkovsky; 11. wall and floor of Tsiolkovsky.

berg (Fig. 4). The curve according to G. S. Shteynberg obviously corresponds better to the actual distribution of craters, although it somewhat overstates the number of impact structures -- it is difficult to accept the fact that there are no volcanic ones among 5-km craters, and in this region the actual distribution coincides almost exactly with G. S. Shteynberg's curve.

The second problem is that the distribution function of secondary fragments by mass and velocity for large craters is also only calculated theoretically. Whereas for fragments, which occur when small craters are formed, one can accept the curve shown by R. G. Neswald, it is difficult to forecast the behavior of this

First, the dependence of the size of the impact crater on the mass and speed of the meteorite is only known for small bodies. This dependence is calculated theoretically for craters larger than 1 km. If one takes the mean speed at impact as equalling 20 km/sec, then for a mass on the order of 10^{10} g, the size of the crater is (according to various authors): 10 km (Hartmann, 1965), 20 km (Stan-yukovich, Bronshten, 1960), and 10 and 5 km (Shteynberg, 1969). In this last work it was stated that large meteorites explode practically on the surface. Judging by the relatively shallow depth of most large meteorite craters on Earth, the correction by G. F. Shteynberg is reliable. In any case, by taking the curve by G. S. Hawkins as the basis for characteristics of a meteorite flux and accepting the speed of bodies during impact as equalling 20 km/sec, one can compile graphs of the frequency of impact craters on one unit of area over 3 billion years. On a logarithmic scale, these graphs look almost like straight lines with close angles of inclination. However, the number of craters of one diameter, according to W. K. Hartmann, is approximately 20 times greater than the number of craters according to G. S. Shteyn-

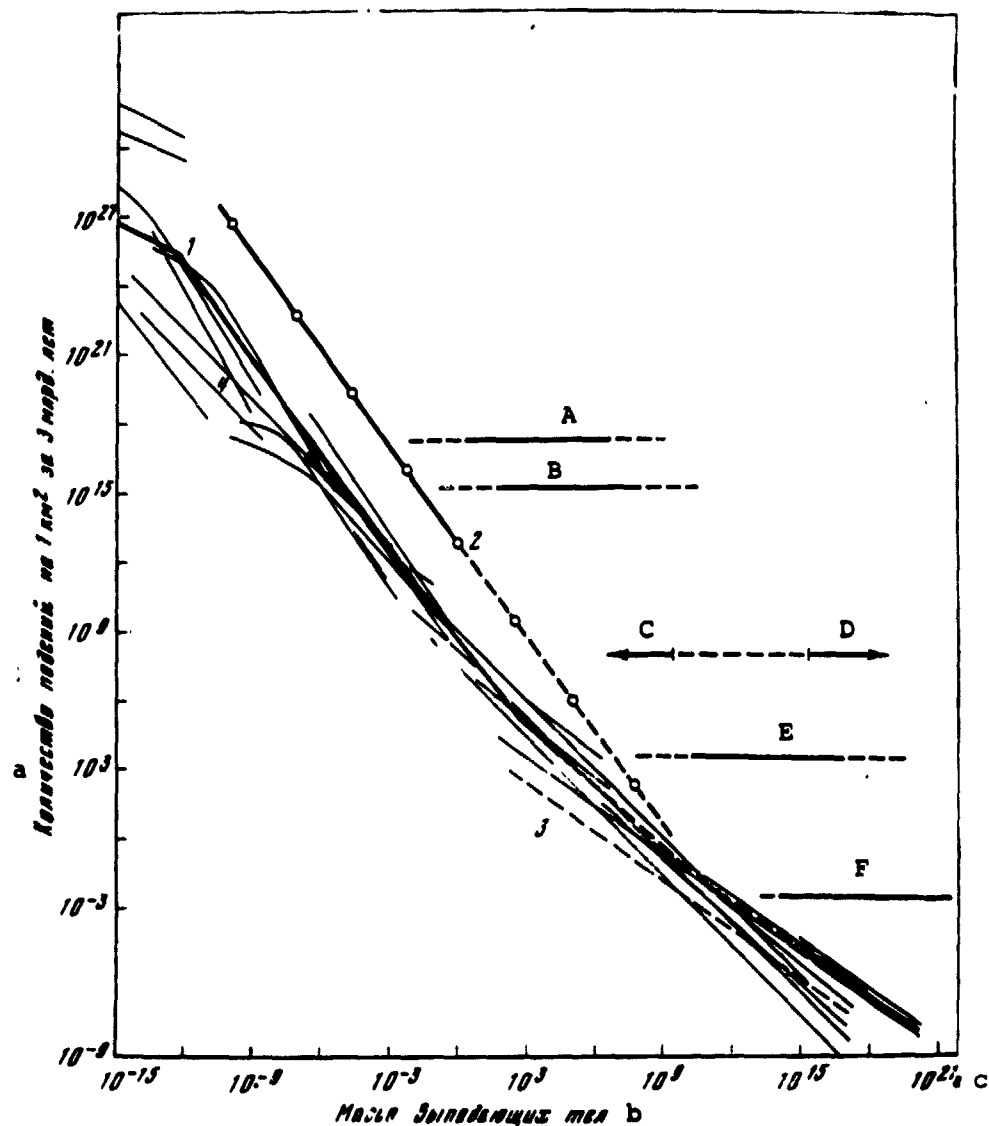


Fig. 3. Different estimates of the values of a meteorite flux: 1. the curve by G. S. Hawkins, taken as the mean; 2. the density curve of secondary fragments on the Moon's surface; 3. comet flux; 4. estimates of the meteorite flux shower by various authors; A. Visual observation range; B. areas of falls and finds of meteorites; C. the break-up area of meteorites in the atmosphere; D. by a test of the atmosphere by large bodies; E. craters excavated; F. asteroids according to telescopic measurements. Dotted line -- insufficiently validated intervals.

Key: a. Number of falls over 1 km² during 3 billion years; b. Mass of falling bodies; c. 10²¹ g

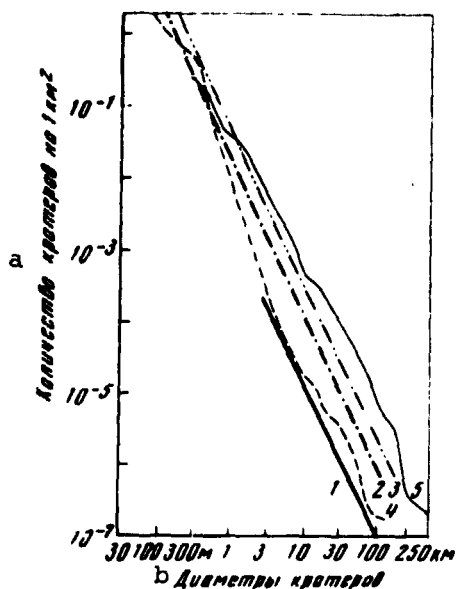


Fig. 4. Density of post-mare craters, calculated by various authors: 1. according to G. S. Shteynberg; 2. according to K. P. Stanyukovich and V. A. Bronshten; 3. according to W. K. Hartmann. For comparison are shown: 4. the actual density of craters on lunar maria and 5. the same on the highlands. The actual distribution corresponds mainly to a curve compiled according to information by G. S. Shteynberg; deviations in the density of craters from the normal distribution can be seen for diameters of 10-100 km.

Key: a. Number of craters over 1 km²;
b. Diameter of craters

curve for fragments with a mass of 10⁷-10⁸ g and above. However, it must be noted that in works on the statistics of craters a considerable number of craters, thought to be secondary ones, are excluded from the calculations (elongated craterlets with small walls and directed ejecta); their diameters are tens and hundreds of meters, and, for the first, sometimes kilometers. For example, E. H. Walker (1967) believes that secondary craters with a diameter greater than 100 m hardly distort the distribution of primary craters. Apparently, the majority of craters visible through a telescope are primary ones.

In spite of the relatively wide divergence of information, the graphs obtained should in some way reflect the actual situation, and some conclusions can be made from them. Attention should be paid to the behavior of a curve showing the distribution of craters in maria (see Fig. 2). It is relatively flat for diameters from 30 to 300 m, and noticeably steeper from 300 m to 10 km; in this interval it is almost straight-line. Between diameters from 10-12 to 20 km, there are many craters, and, from 20-26 to 70 km, the density of craters increases even more. If one reckons that a section from 300 m to 10 km is the normal distribution of impact craters, the flat slope of a curve in the small diameter range can be explained by the fact that saturation has been reached, where an increase in the number of craters with a decrease of diameter slows down due to erosion and the overlapping of old craters by newly

formed ones (Collins, Smith, 1967; Chapman, 1968; Chapman et. al, 1970). The abundance of craters with a diameter greater than 10 km is explained mainly by the fact that in the interval there is an increase in the number of volcanic forms in comparison with

meteoritic ones. By comparing this distribution with the theoretically calculated one (according to G. S. Shteynberg), it can be concluded that the number of endogenous craters with a diameter of 10-20 km is at least equal to the number of meteoritic ones; and for craters with a diameter of 20-26 to 70 km, 2-2.5 times greater than for meteoritic ones.

Recently, W. K. Hartmann and J. A. Wood suggested an interesting explanation for similar curves (Hartman, Wood, 1971). They believe that at the moment when maria are filled in, effusives overlap all craters which have less than a certain diameter. The large craters remaining on the surface as a result are "added together" with the newly formed ones, and in this way an abundance of large craters appears on graphs. Undoubtedly, this process should affect the distribution of craters. However, whereas craters with a diameter of approximately 10 km remained uncovered in the maria, the thickness of lava did not exceed the first hundreds of meters (which is comparable to the height of walls of these craters), whereas in fact the thickness of mare lava is much greater.

The number of craters on sections of different ages can vary by an order of 2-3. Hence, in Mare Claritas, the density of craters is 2-3 times lower than in an "average" mare, obviously due to its relatively recent age. However, there is an abundance of those greater than 10 km for it. There is a noticeable, but not as clearly expressed, abundance of craters greater than 10 km on the graph for the highlands; apparently, here there is one meteorite crater for one volcanic one. The same bend is seen for the highland region around Mare Orientale. On curves for the highlands, there is another bend for walls of Alphonsus and the Tycho and Copernicus craters -- from 0.7-0.8 to 1.5-2 km; the number of craters with larger diameters exceeds the mean values for these ranges.

In general, the irregularities of increase in the number of craters as their diameters are reduced is more noticeable when the accuracy of the calculation is increased, that is, when the grouping interval is reduced: the more accurately developed the crater according to diameter, the more often the points lie on the curve and the more clearly noticeable are the deviations from the normal logarithmic curve (Florenskiy et al., 1969; Greeley, Gault, 1970).

For the highlands as a whole, there is a curve which differs noticeably from all others. As the diameters increase, the density of highland craters also increases; whereas in the range of hundreds of meters, this density is close to the "mean mare," for craters with a diameter in kilometers and tens of kilometers, their density increases 20-30 times. The inclination of the "highland" curve as a whole is flatter than the "mare," and possibly approaches

the saturation threshold. The number of craters itself can be explained by the fact that, up to a moment 3 billion years ago, the intensity of bombardment was much higher than today. Another version is the great role of crater-forming volcanism on the highlands in comparison with the mare or the significant role of this volcanism in a period earlier than 3 billion years ago. Possibly all three reasons occurred simultaneously.

Differences in the crater density in individual maria are not uniform for craters of different diameters. Fig. 5 shows this tendency graphically: as the age of the maria increases, the number of craters grows more quickly, and their diameter is larger. There are two explanations for this: 1) in the early stages of the formation of maria there were more large fragments in the meteorite flux; 2) the abundance of large craters formed by volcanism, which lasted longer (or more intensely) on the maria, formed earlier. The second explanation is more probable.

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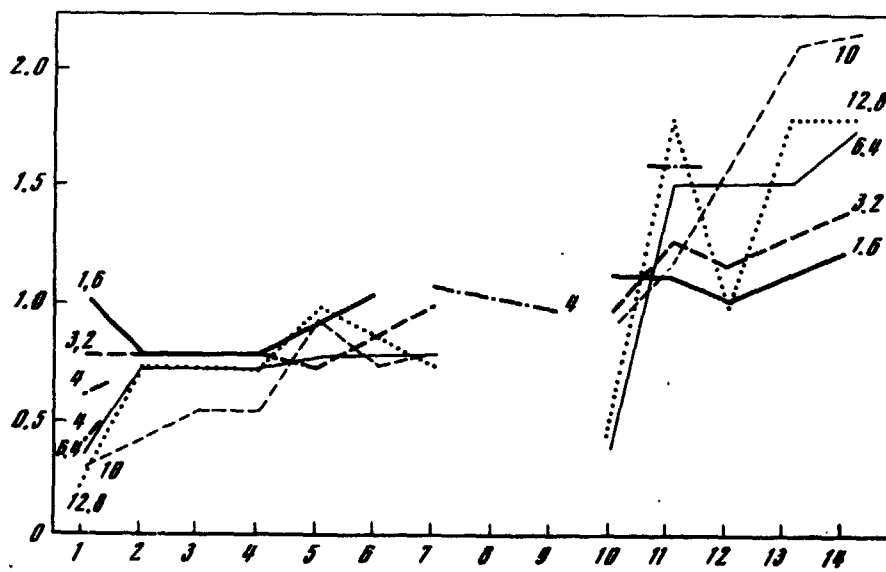


Fig. 5. Density of postmare craters on different maria according to a summary by W. K. Hartmann (1967). The curves show data of different authors; the figures near the curves show the diameter of the smallest craters (in km) included in the calculation. Along the vertical is the relative density of craters if one accepts the crater density of Mare Orientale as one unit; along the horizontal are different mare: 1. Mare Claritas, 2. Sinus Epidemiarum, 3. Mare Humorum, 4. Mare Nubium, 5. Mare Crisium, 6. Oceanus Procellarum, 7. Mare Imbrium, 8. Mare Orientale, 9. Mare Cognitum, 10. Mare Nectaris, 11. Mare Frigoris, 12. Mare Fecunditatis, 13. Sinus Somniorum, 14. Mare Tranquillitatis.

Hence, existing data on meteorite and impact craters allow conclusions to be made which are of significant value when interpreting lunar forms.

1. The possibility of the formation of central peaks in meteorite craters has been insufficiently proved. On the other hand, there is no proof that they did not occur in craters with a diameter greater than 10 km. Therefore, a simple central peak in a lunar crater does not show the origin of the crater, especially if one takes into account the possibility of volcanic conversion of the primary impact crater.

Large fractures and a great amount of volcanism are not linked with proven and assumed terrestrial meteorite craters. They are almost circular; elongated explosive craters or chains of craters without abutting closures are unknown.

2. The distribution of the majority of lunar craters by size and frequency corresponds to the frequency distribution of masses in a meteorite flux and, apparently, is a function of the latter; this is a fact favoring the theory of the impact origin of the majority of craters. However, this majority is created due to small craters. If one differentiates craters by diameter, among forms with a diameter greater than 1 km there is an abundance of apparently endogenous craters, on some curves, and, with diameters from 10 to 70 km, the number of endogenous craters on the Moon is at least equal to the number of meteoritic ones, or even exceeds it.

3. One can estimate the age of these regions relative to other areas according to the density of craters on individual parts of the Moon. But their absolute age can only be shown in a first approximation, since the intensity of the meteorite flux at that time was unknown, as is the exact number of endogenous craters over a given area.

Volcanic Forms on the Lunar Surface

Domes

Circular and isometric dome-like elevations on the flat mare surface were unknown before the flights of spacecraft (Rae, 1963, 1966; Cook, 1966; and others). Many hundreds of such domes are visible through a telescope. Their average diameter is 5-15 km, and sometimes 40 km; their height is from tens to hundreds of meters. Complex domes have been described -- with summit craters with collapsed rims and central peaks. The domes have gentle slopes (first degrees) and an indistinct boundary with the surrounding surface. Sometimes they merge gradually with the surface. Large forms of this type are somewhat distinct, owing to their compressed surface and relatively distinct boundaries

(at least on one side: for example, the dome in the strait between Mare Claritas and Mare Imbrium). The domes do not normally stand out from the mare surface by their brightness; sometimes they are lighter than the mare, and, in other cases, in extreme ray conditions, darker (southeast Copernicus).

The flights of spacecraft showed many new dome-like forms on the maria and inside craters. It appeared that their surface usually differs from the surrounding mare surface in that it is flatter, or, on the contrary, has a larger number of small craters. Some of the domes have craters or small steep knolls on their summits ridges; (McCauley, 1968). There is a link between domes and mare ridges; transitional forms between one and the other are frequent. The most characteristic domes are west of the Marius crater, where there are approximately 150 domes with diameter from several hundreds of meters to 20-30 km on an area of approximately 10,000 km² (Fig. 6). /26

There are three interpretation of the domes: a) heaps of ejecta from distant craters; b) "translucent" remains of the ante-mare foundation; c) volcanogenic bulges and accumulations of effusive and pyroclastic material.

The first is removed if one compares the morphology of the domes with structures of these formations which, according to the majority of authors, are ejecta from craters. The circular form, characteristic profile, large summit craters on some small domes, the link with walls and the absence of a link with ejecta of some craters -- all this does not leave any doubt that the domes were formed in situ.

The telescoping of the foundation structure also conflicts with observation. Mainly linear and ring forms are developed on the highlands. When these were inundated, linear and ring crests remain on the surface (Mare Nubium); when further submersion took place, only individual pieces of crests and steeply inclined remains of the foundation with sharp boundaries are seen on the surface. If foundation structures had appeared in the maria in the form of domes, these domes would have been seen everywhere in the half-submerged areas; however, here there are fewer of them than in the deep areas of the maria, and they differ greatly from known telescoped crests and protrusions.

Therefore, there is only one explanation: the domes were formed by volcanism. It is not clear whether they are laccoliths, lava domes or shield volcanoes -- obviously there are different types of domes. It is important to stress that, in spite of the fact that there are no covers, in the majority of cases the endogenous nature of the domes can be reliably maintained.

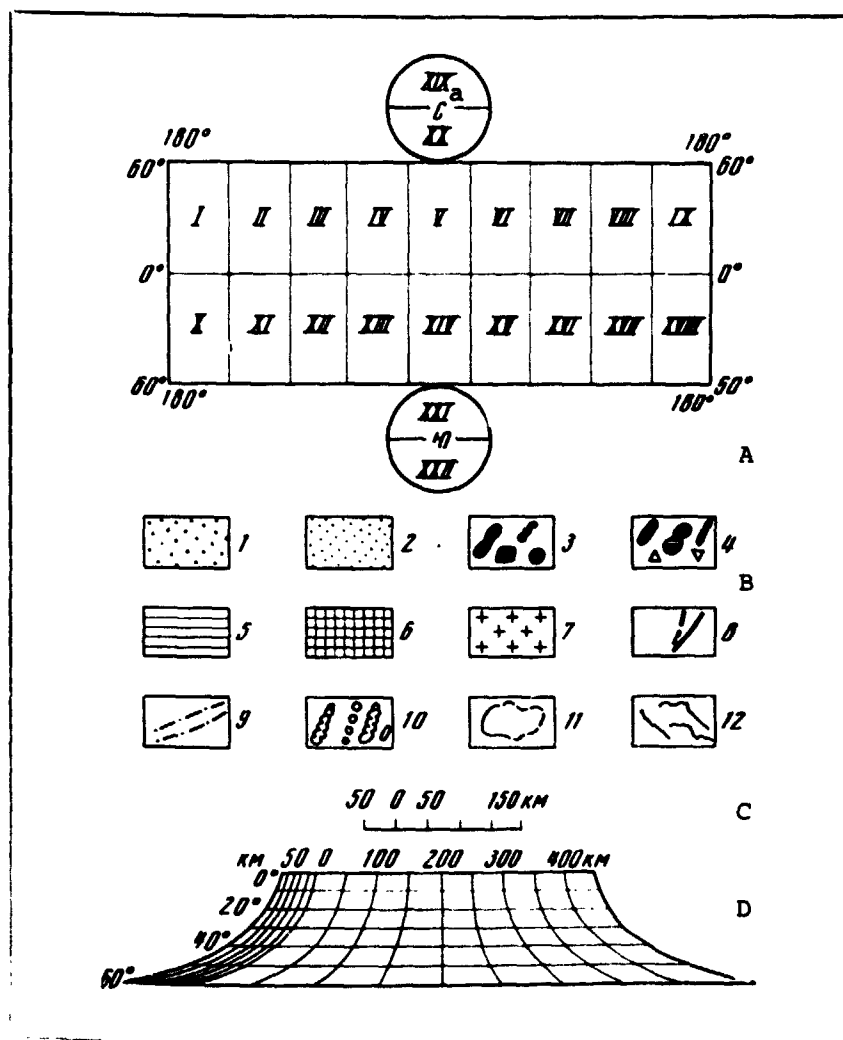
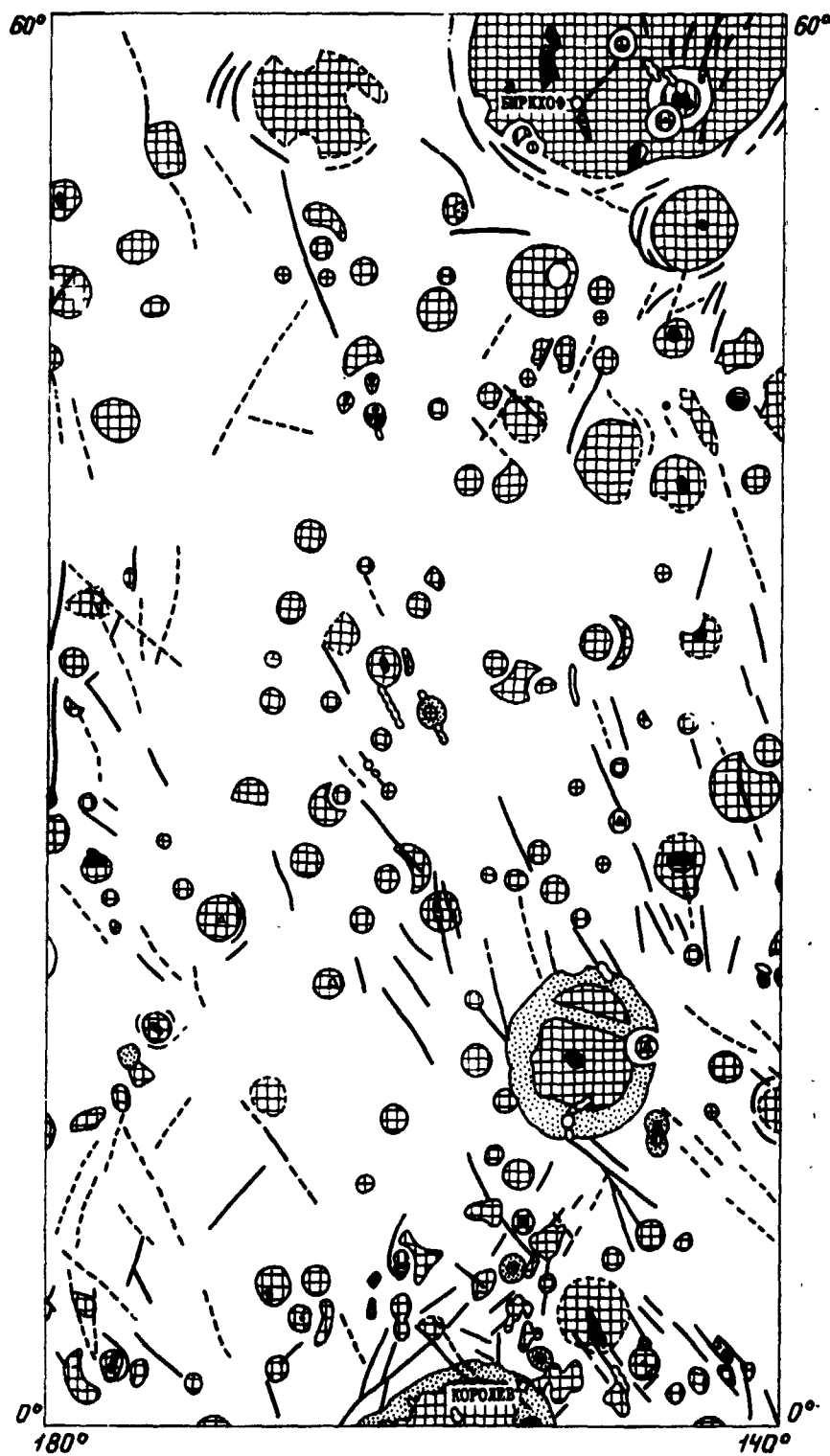


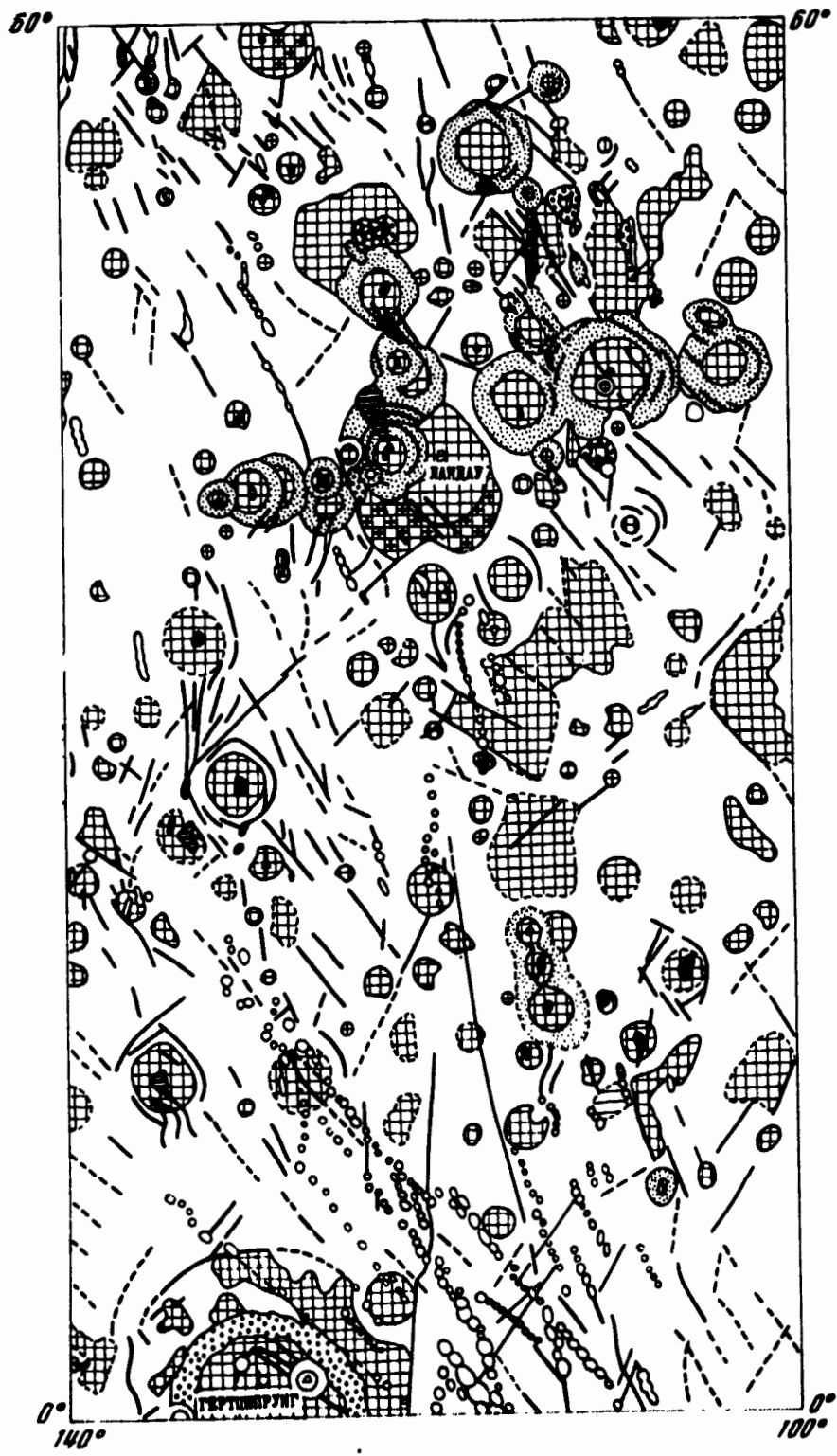
Fig. 6. A map of volcanic forms on the Moon (sheets I-XXII). A. A diagram of the arrangement of map sheets; B. Symbols on the map; 1. craters of volcanic origin; 2. craters of presumably volcanic origin; 3. volcanoes and extrusions; 4. probable volcanoes and extrusions; 5. dark (young) maria; 6. light (old) maria; 7. volcanic regions; (individual structures are not given on this scale); 8. fractures; 9. mare ridges; 10. volcanic craterlets, chains of craterlets and excavation channels; 11. contacts; 12. meandering channels (rilles); C. scale for latitudes 60-90°; D. scale for latitudes 0-60°.

Key: a. N
b. S



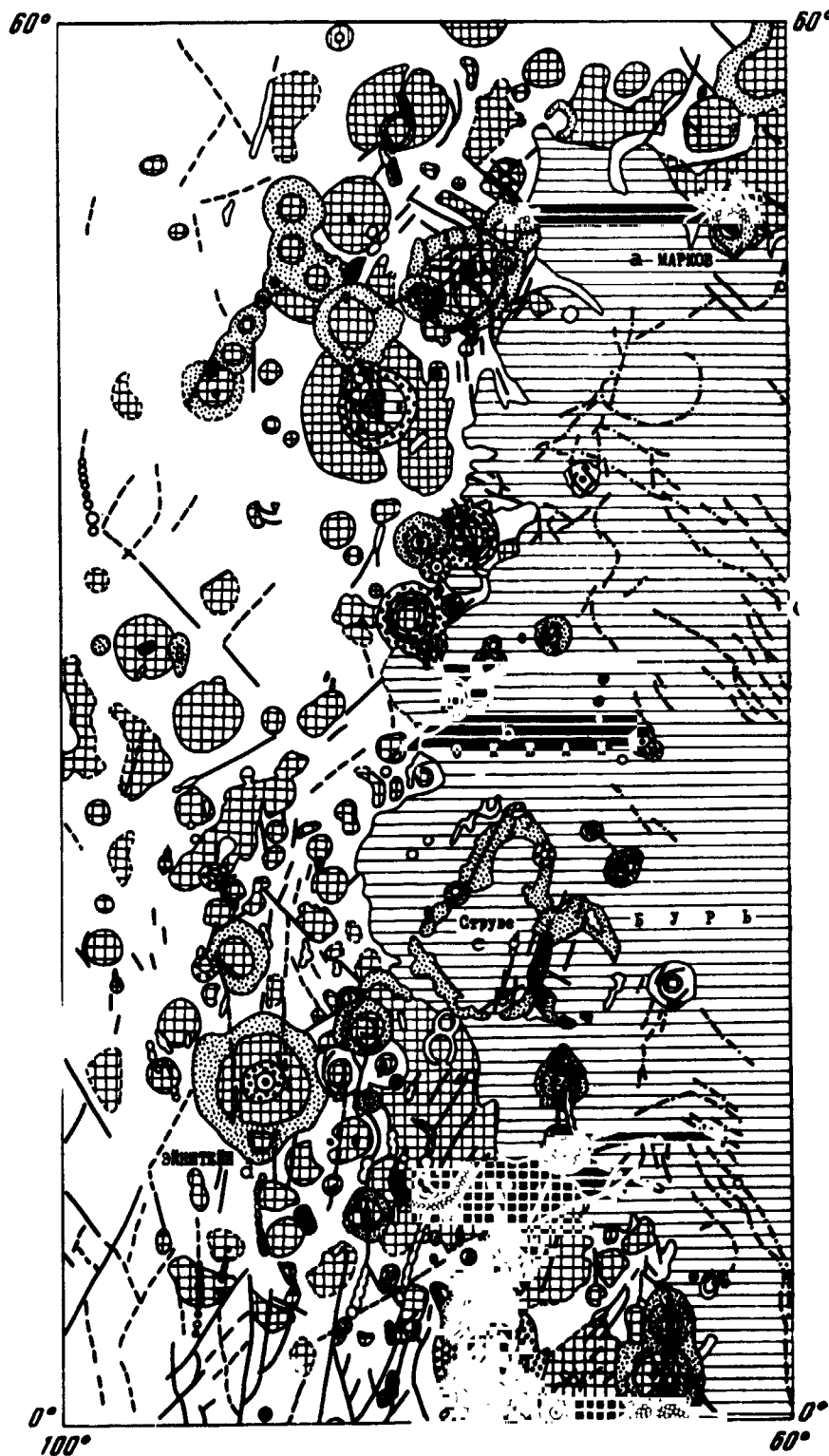
Sheet I.

Key: a. Birkhoff
b. Korolev



Sheet II.

Key: a. Landau
b. Hertzsprung



130

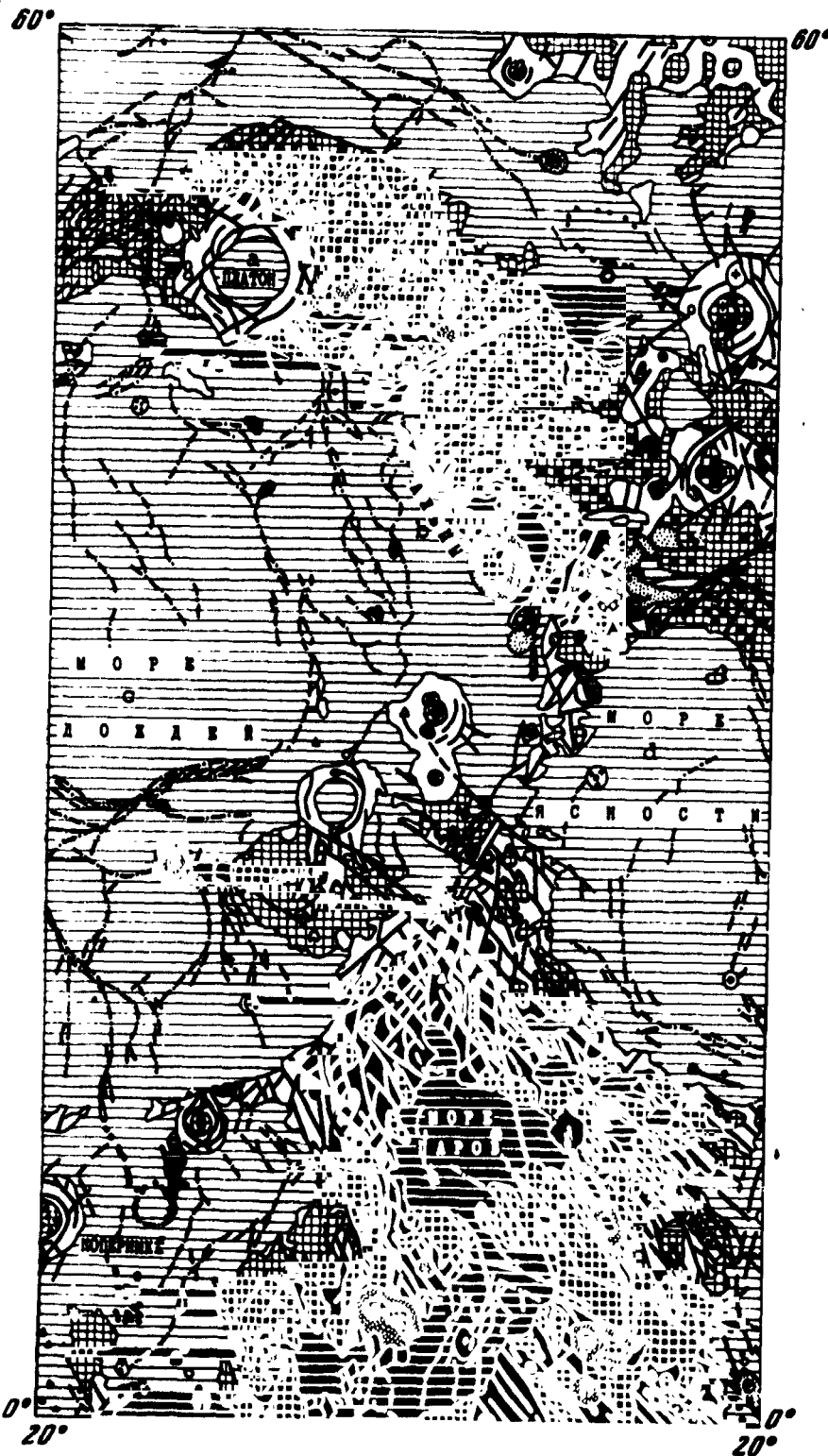
Sheet III.

Key: a. Markov; b. Oceanus Procellarum; c. Struve;
d. Einstein



Sheet IV.

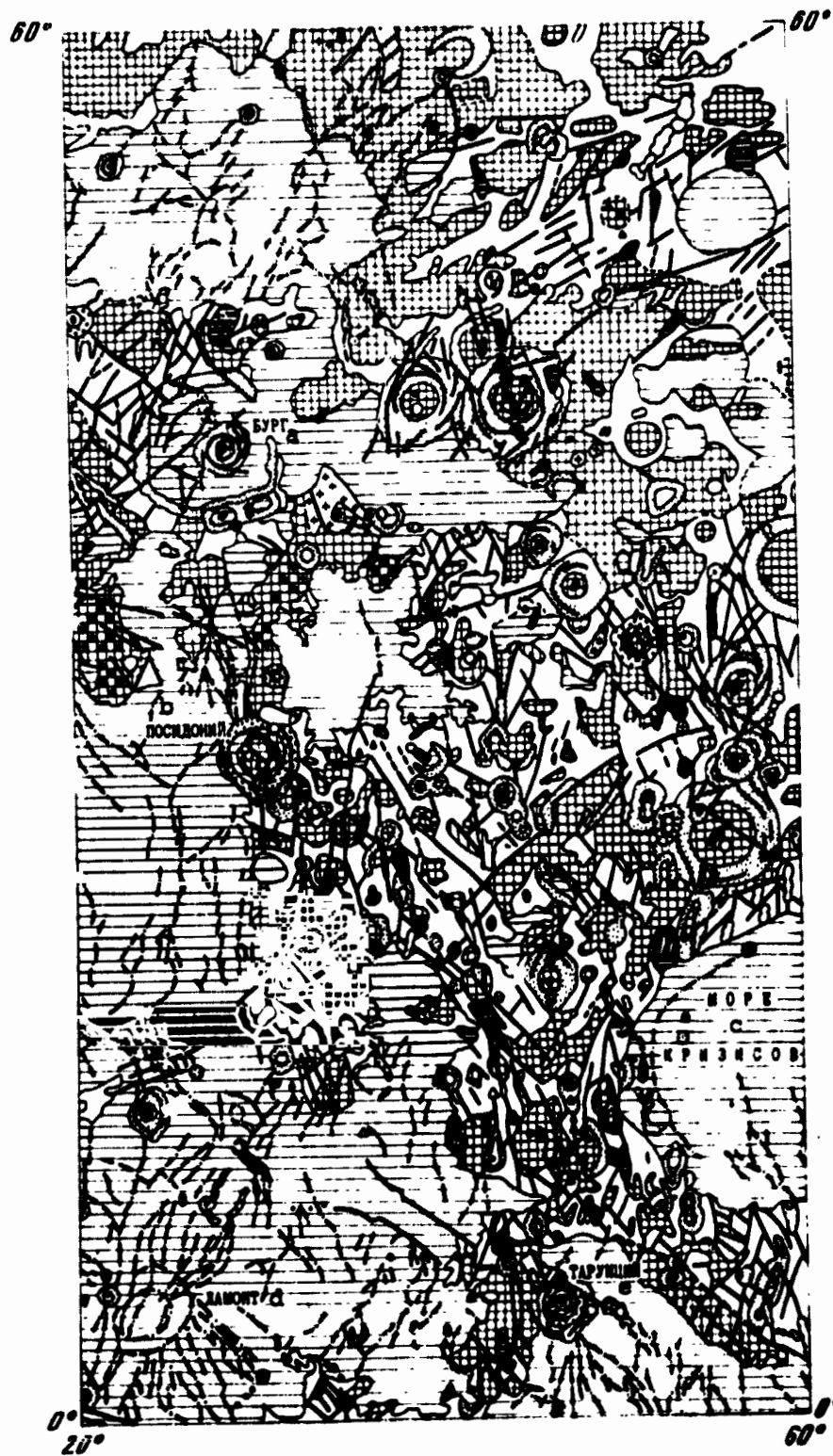
Key: a. Mare Frigoris c. Aristarchus
 b. Sinus Iridum d. Marius



132

Sheet V

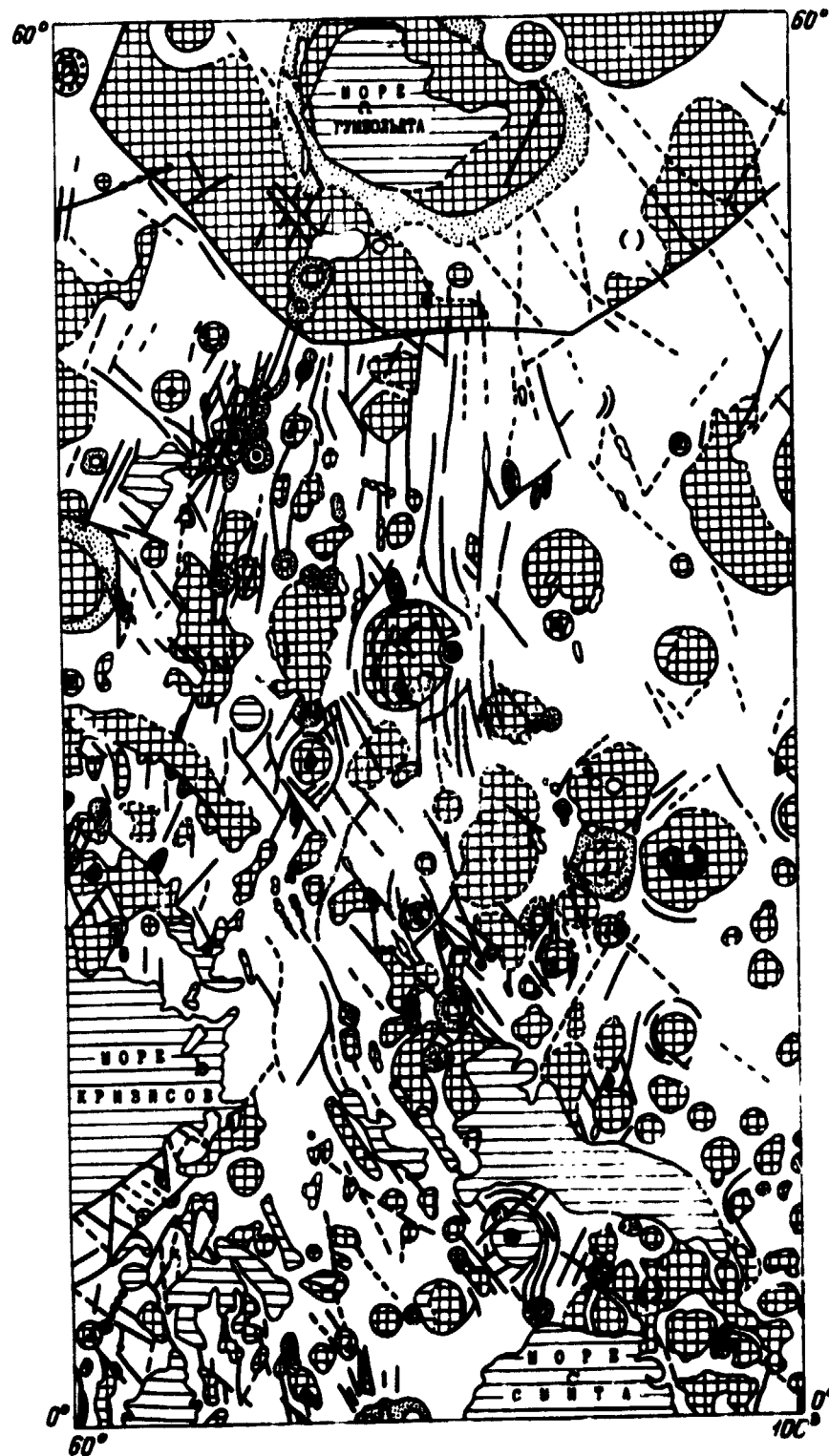
Key: a. Plato c. Mare Imbrium e. Mare Vaporum
b. Alps d. Mare Claritas f. Copernicus



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Sheet VI.

Key: a. Burg
b. Posidonius
c. Mare Crisium
d. Lamont
e. Taruntius



134

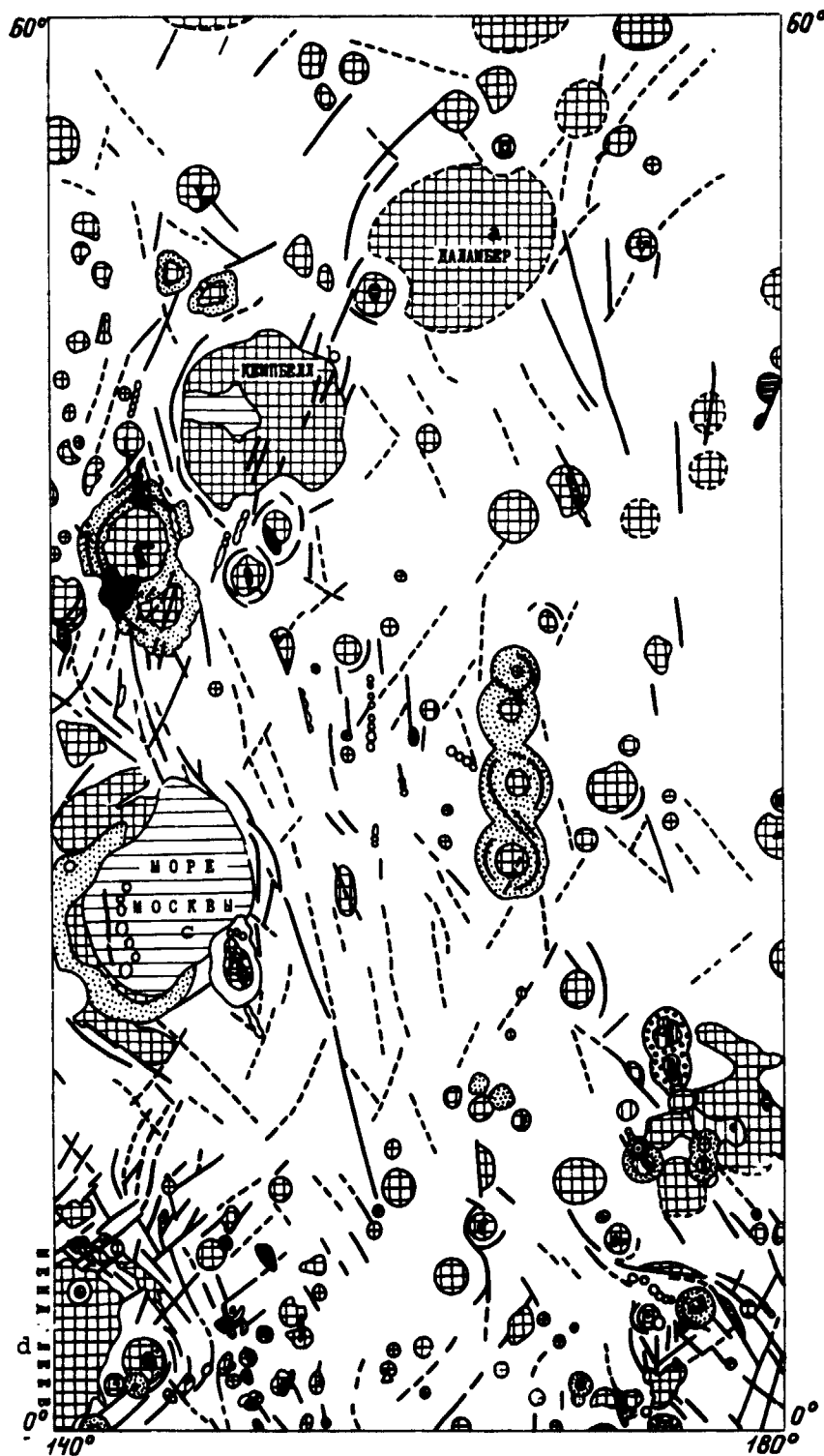
Sheet VII

- Key: a. Mare Humboldtianum
b. Mare Crisium
c. Mare Smythii



Sheet VIII

Key: a. Compton c. Mendeleyev
b. Reimann

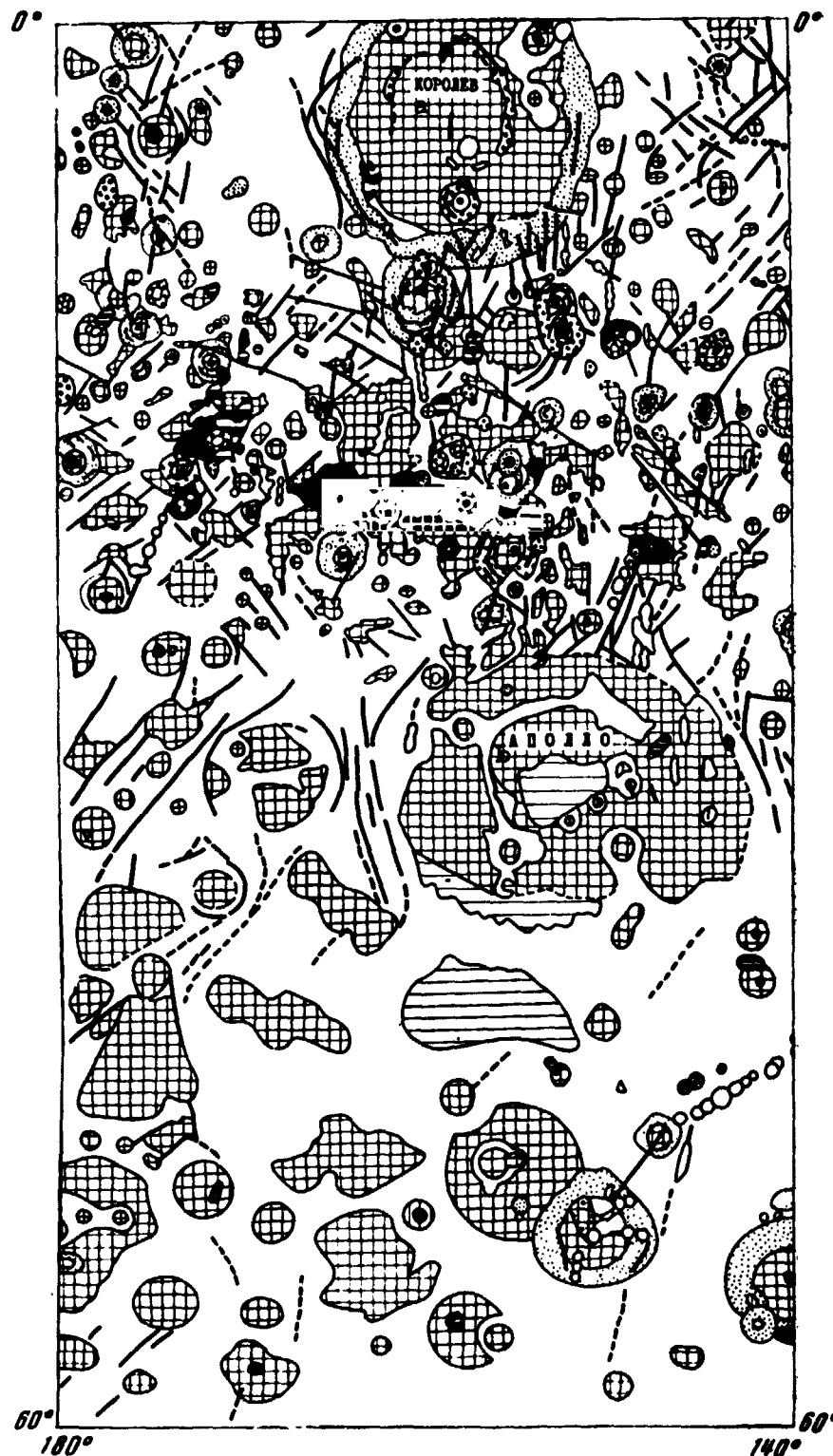


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Sheet IX.

Key: a. D'Alembert c. Mare Moscoviense
b. Campbell d. Mendeleyev

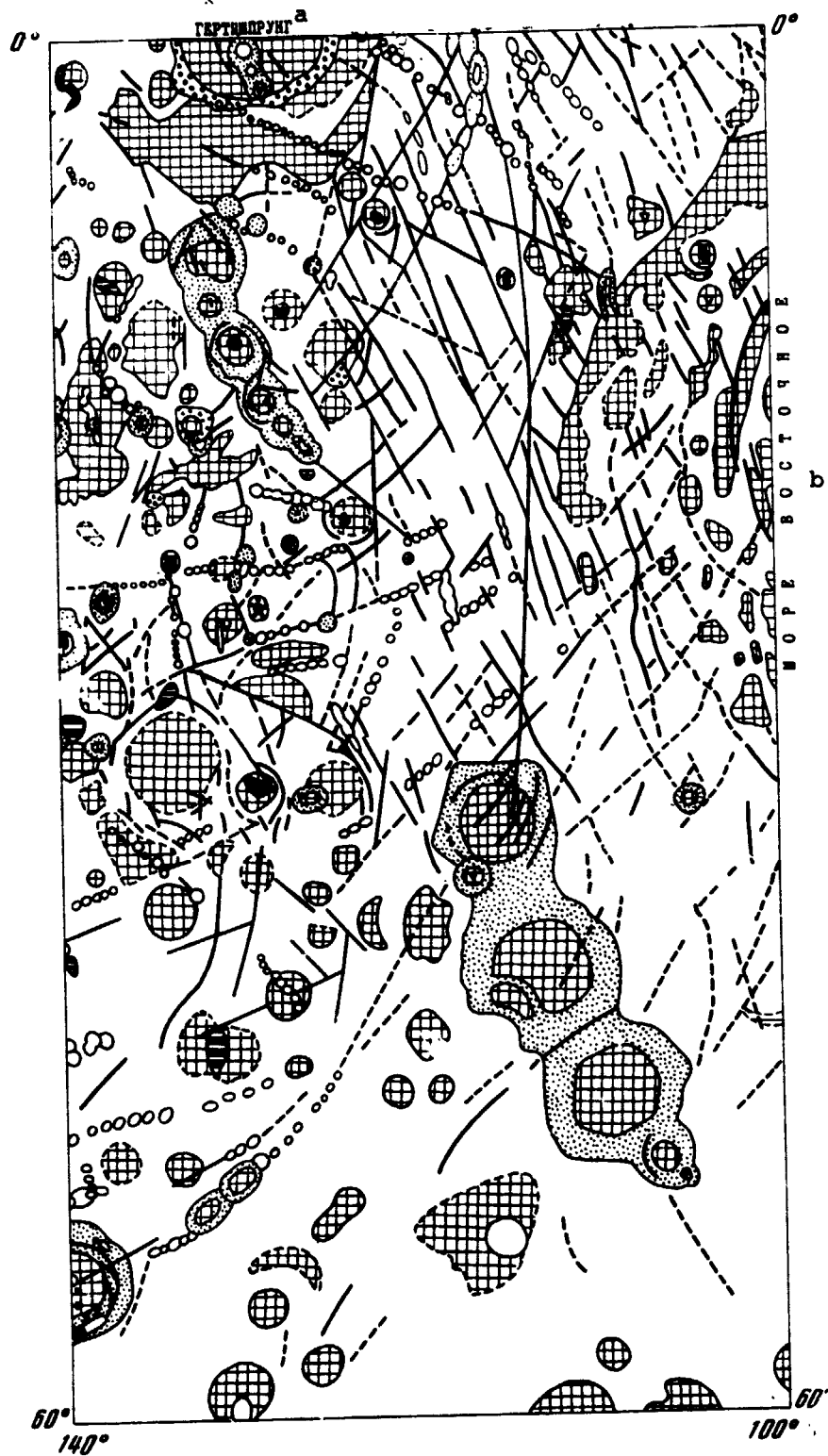
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137

Sheet X.

Key: a. Korolev
b. Apollo



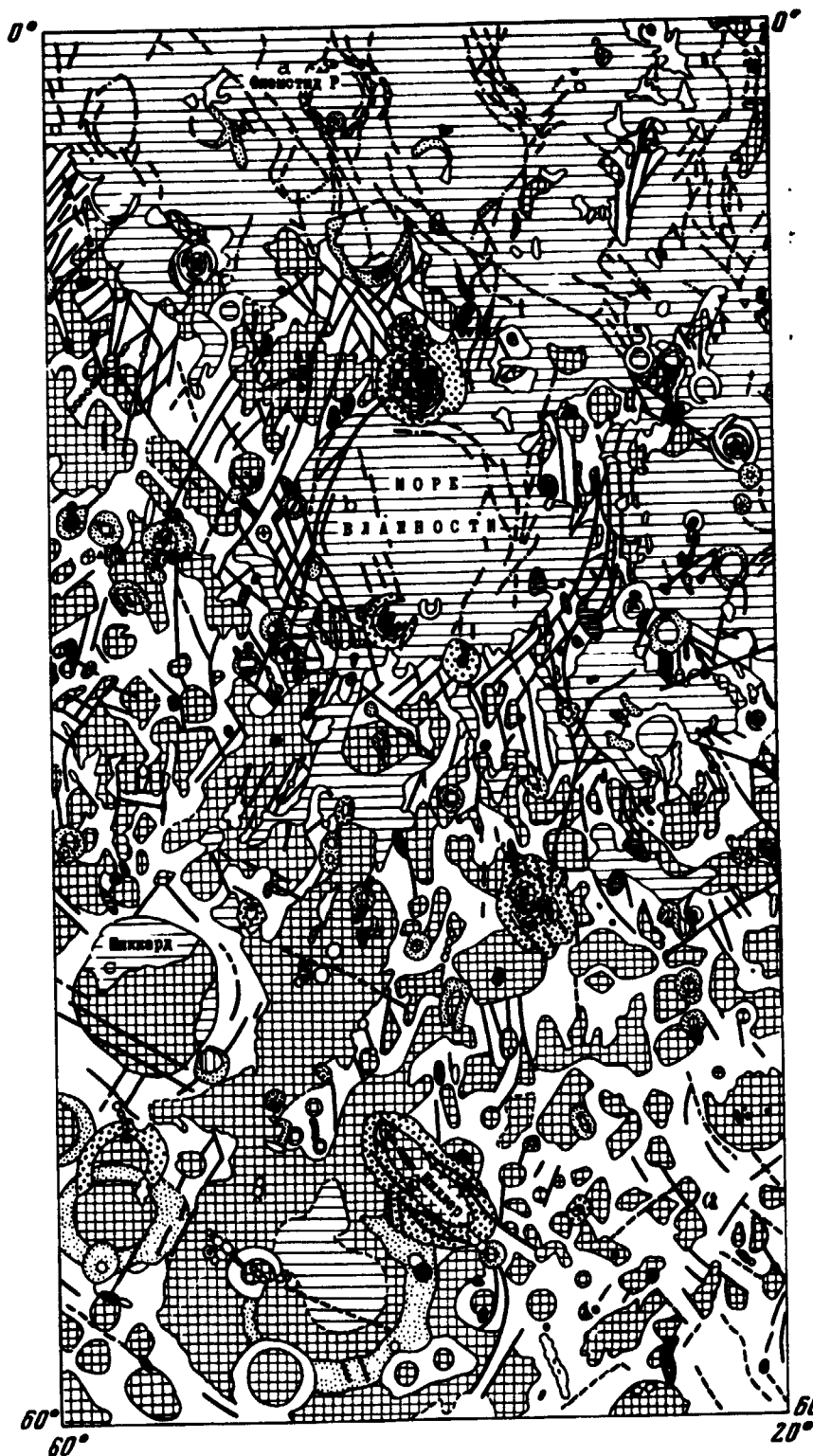
Sheet XI

Key: a. Hertzsprung
b. Mare Orientale



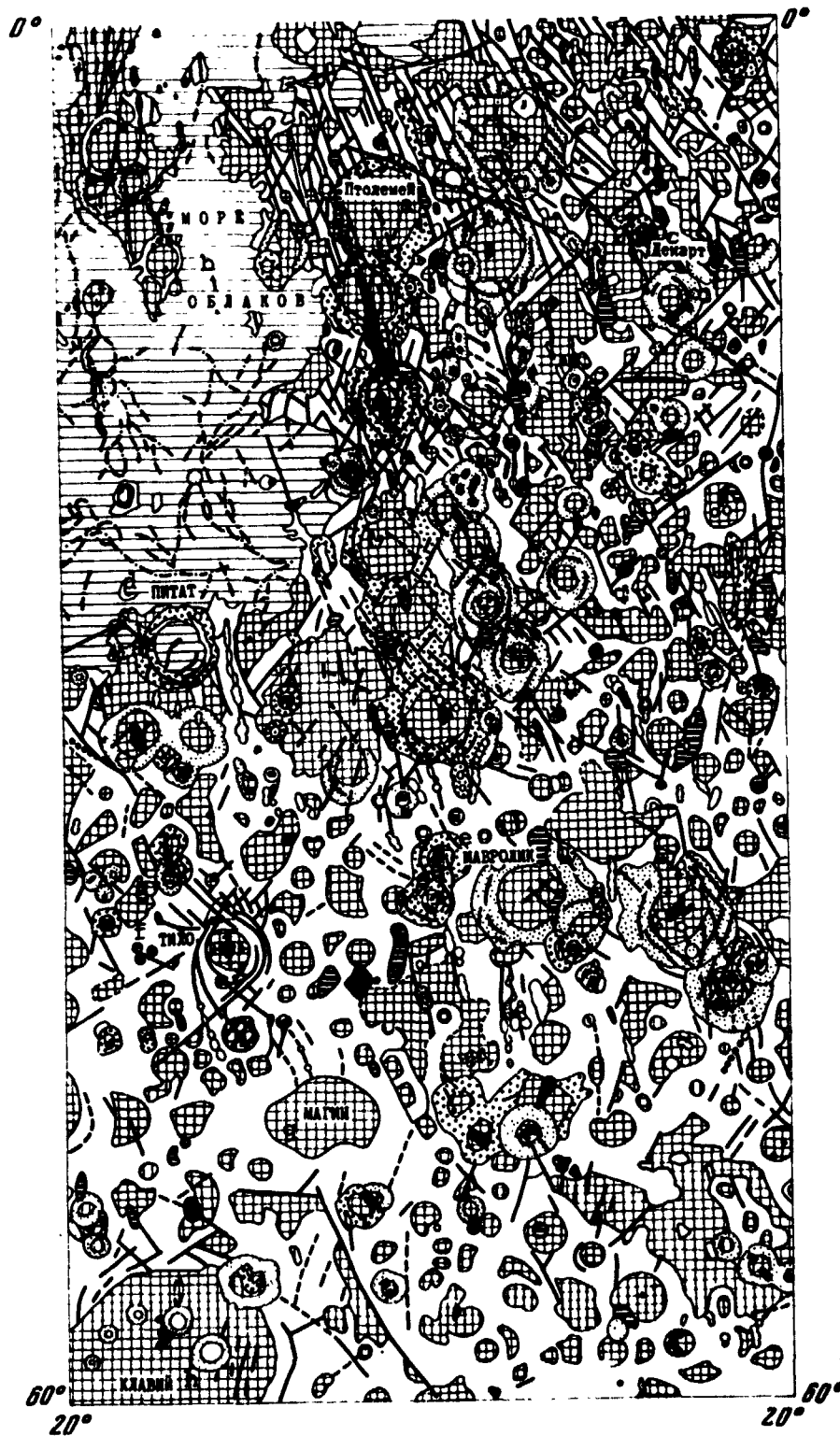
Sheet XII

Key: a. Riccioli
b. Mare Orientale
c. Inghirami



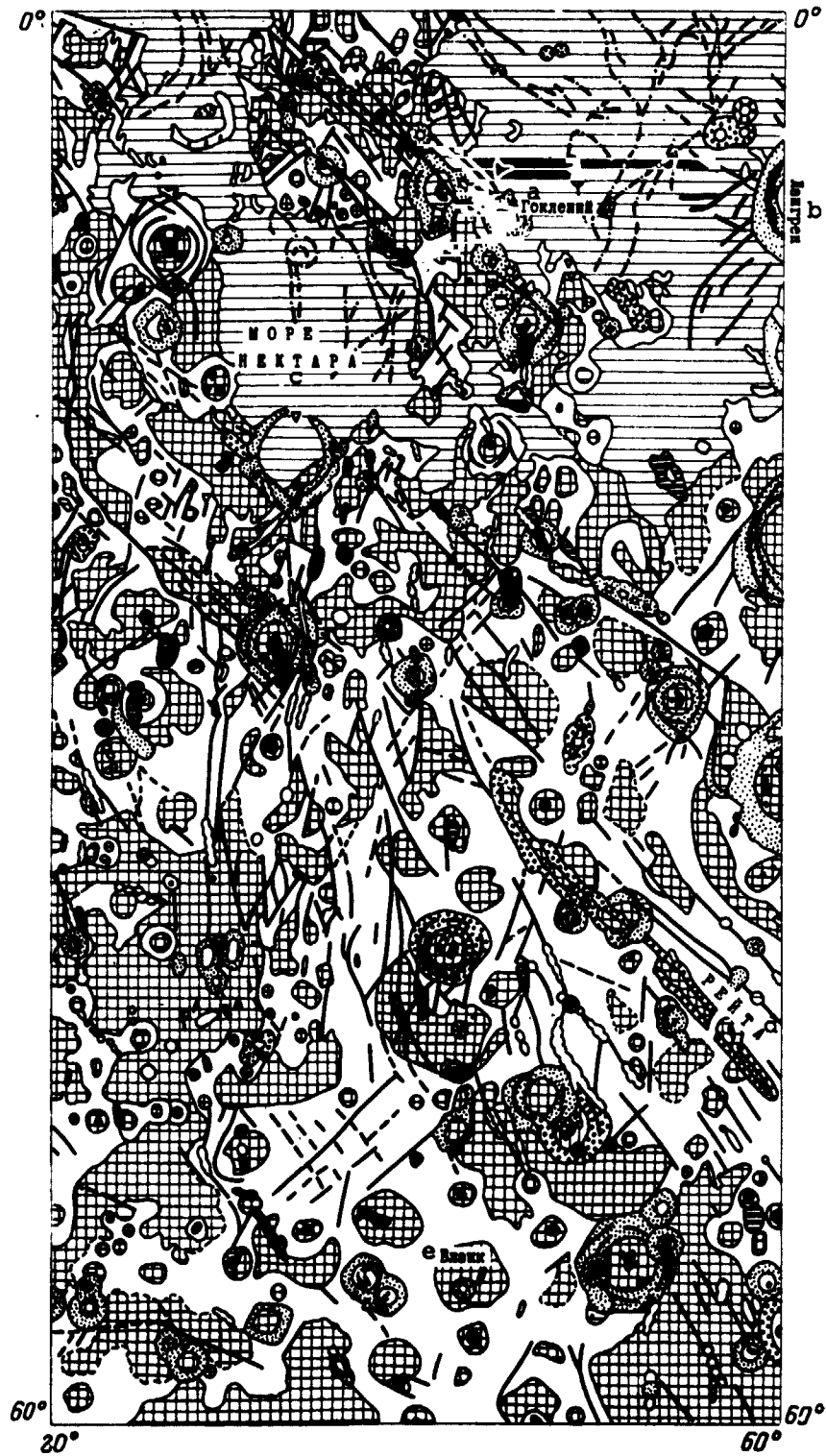
Sheet XIII

Key: a. Flamsteed c. Schickard
 b. Mare Humorum d. Schiller



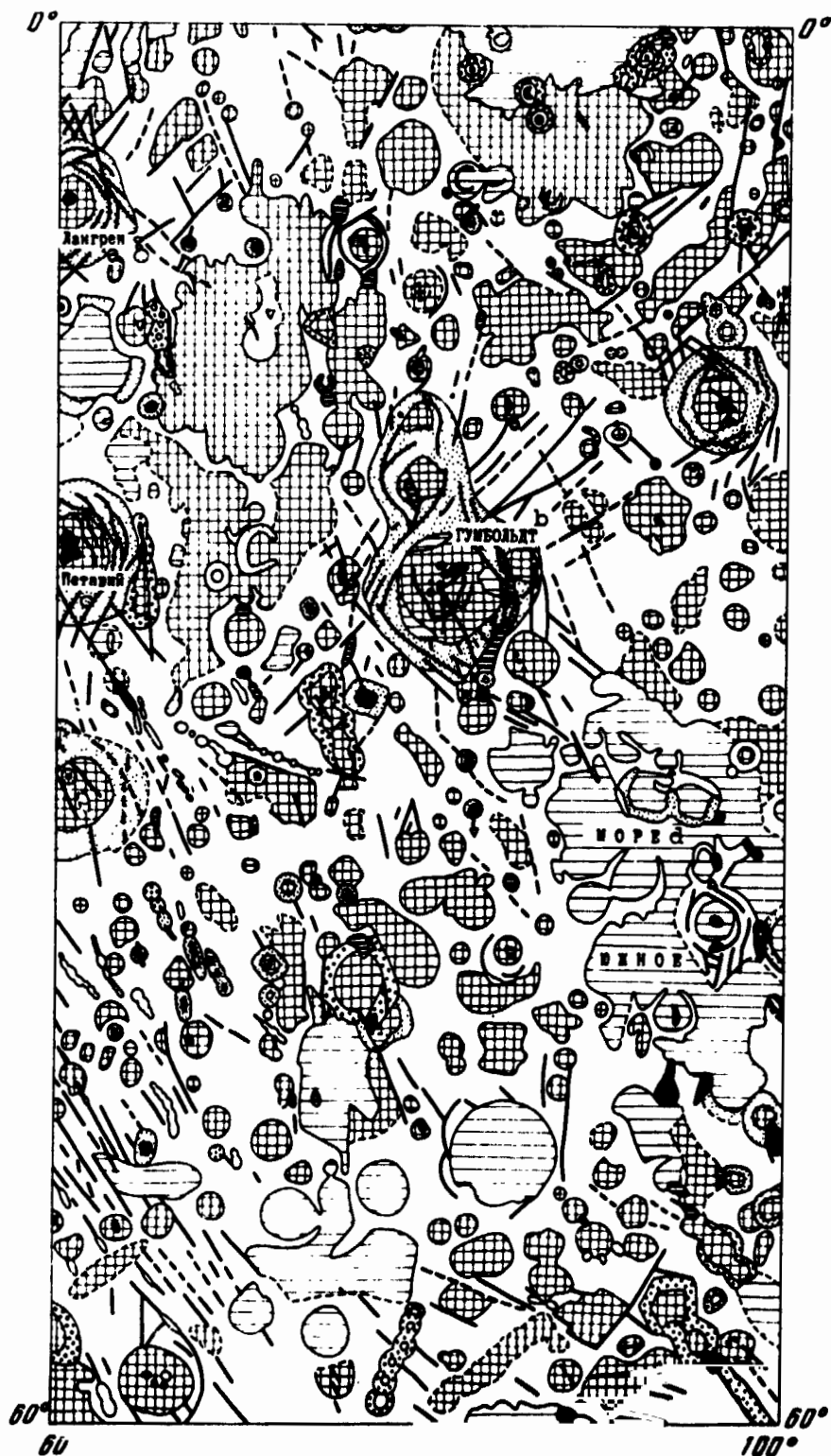
Sheet XIV

Key:	a. Ptolemaeus	d. Pitatus	g. Maginus
	b. Mare Nubium	e. Maurolycus	h. Clavius
	c. Descartes	f. Tycho	



Sheet XV

Key: a. Goclenius c. M're Nectaris e. Vlacq
b. Langrenus d. Rheita



43

Plate XVI

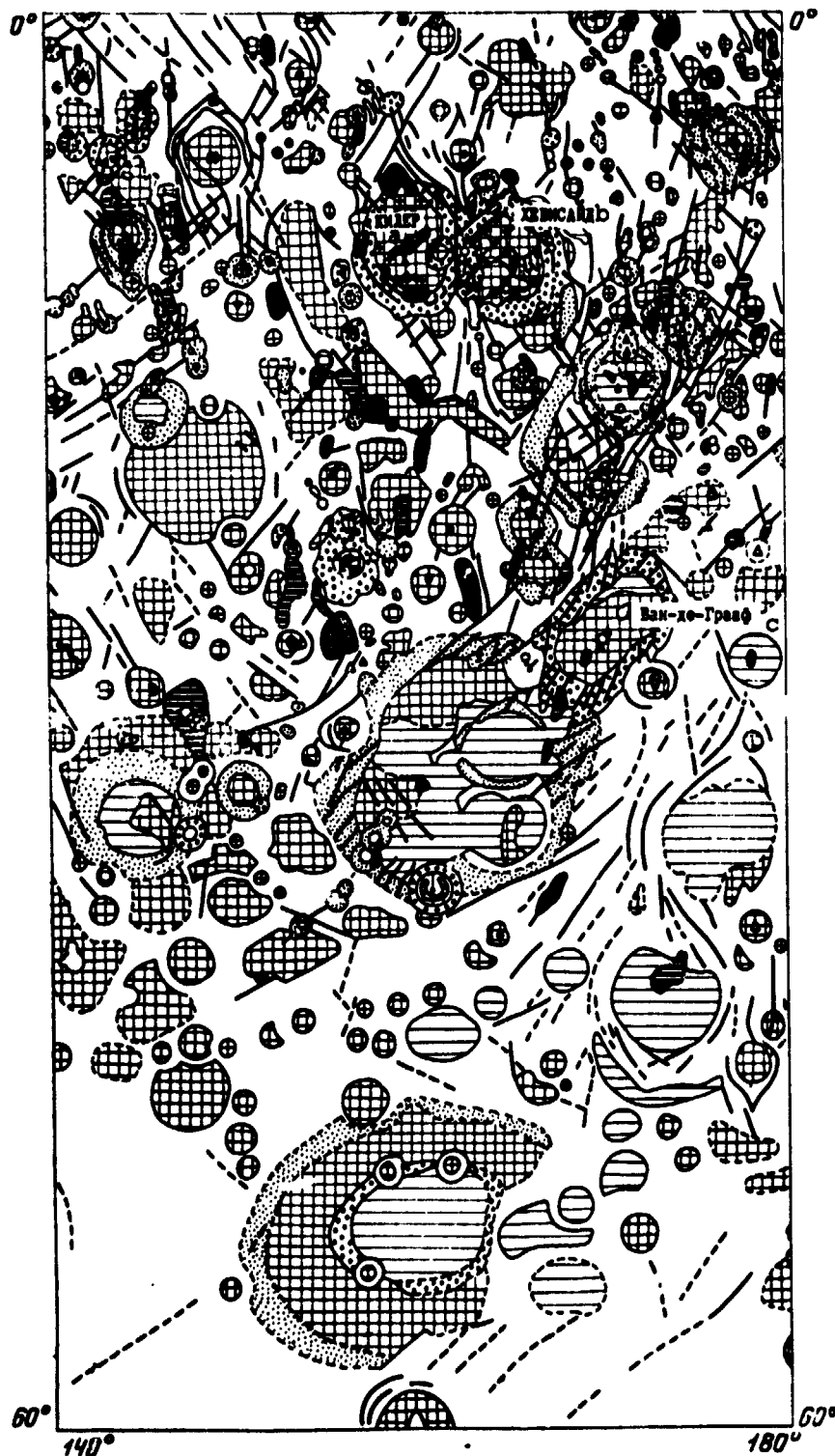
Key: a. Langrenus c. Petavius
b. Humboldt d. Mare Australe



44

Sheet XVII

Key: a. Tsiolkovsky
b. Milne

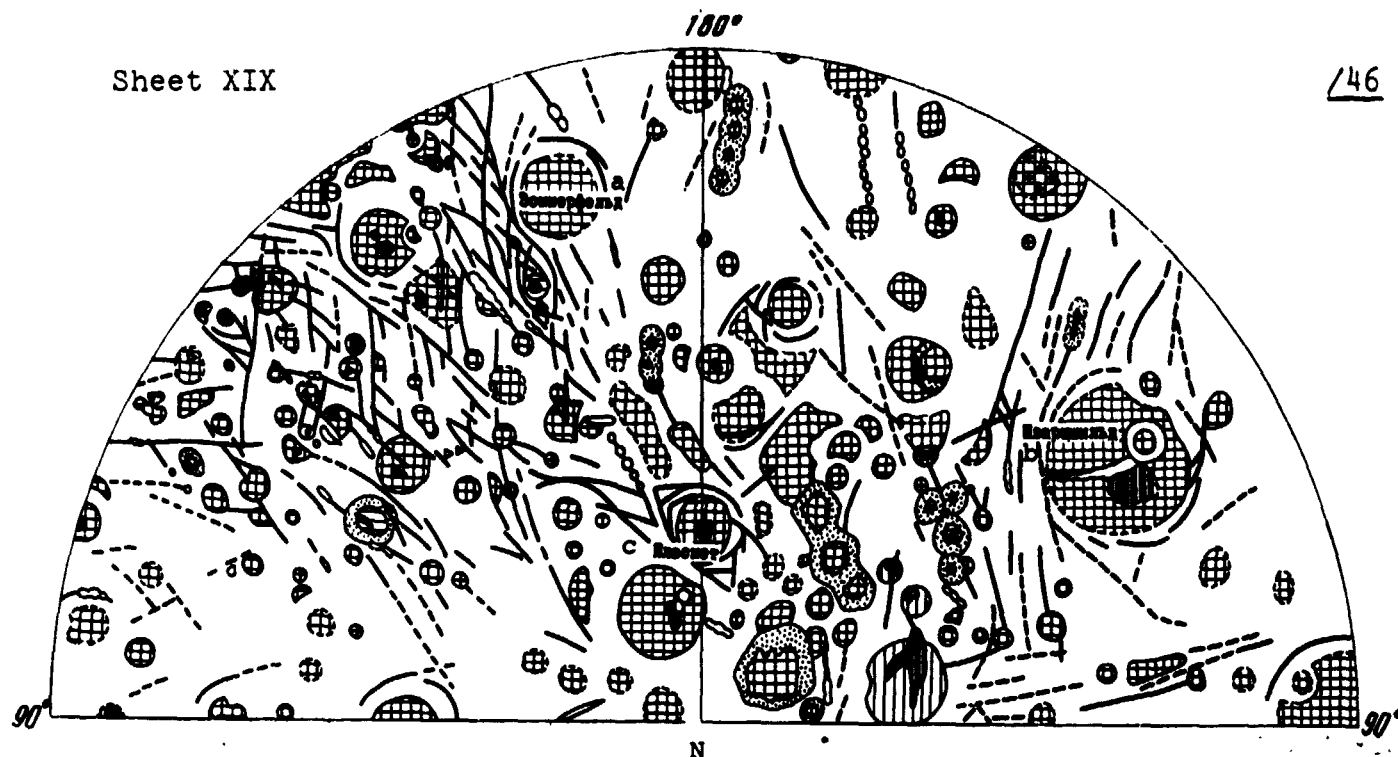


Sheet XVIII

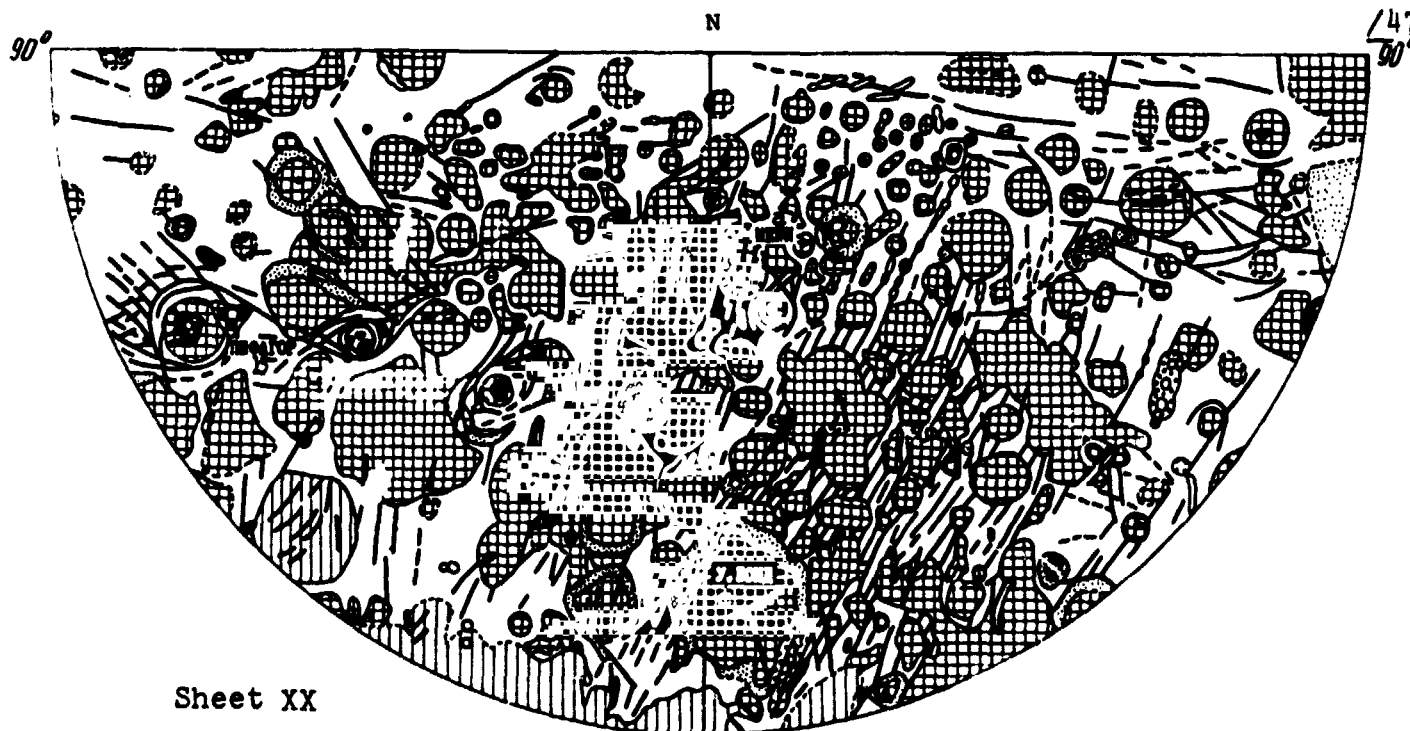
Key: a. Keeler c. Van de Graaf
 b. Heaviside

Sheet XIX

46



Key: a. Sommerfeld; b. Schwarzschild; c. Plasket



Sheet XX

Key: a. Main; b. Pythagoras; c. W. Bond

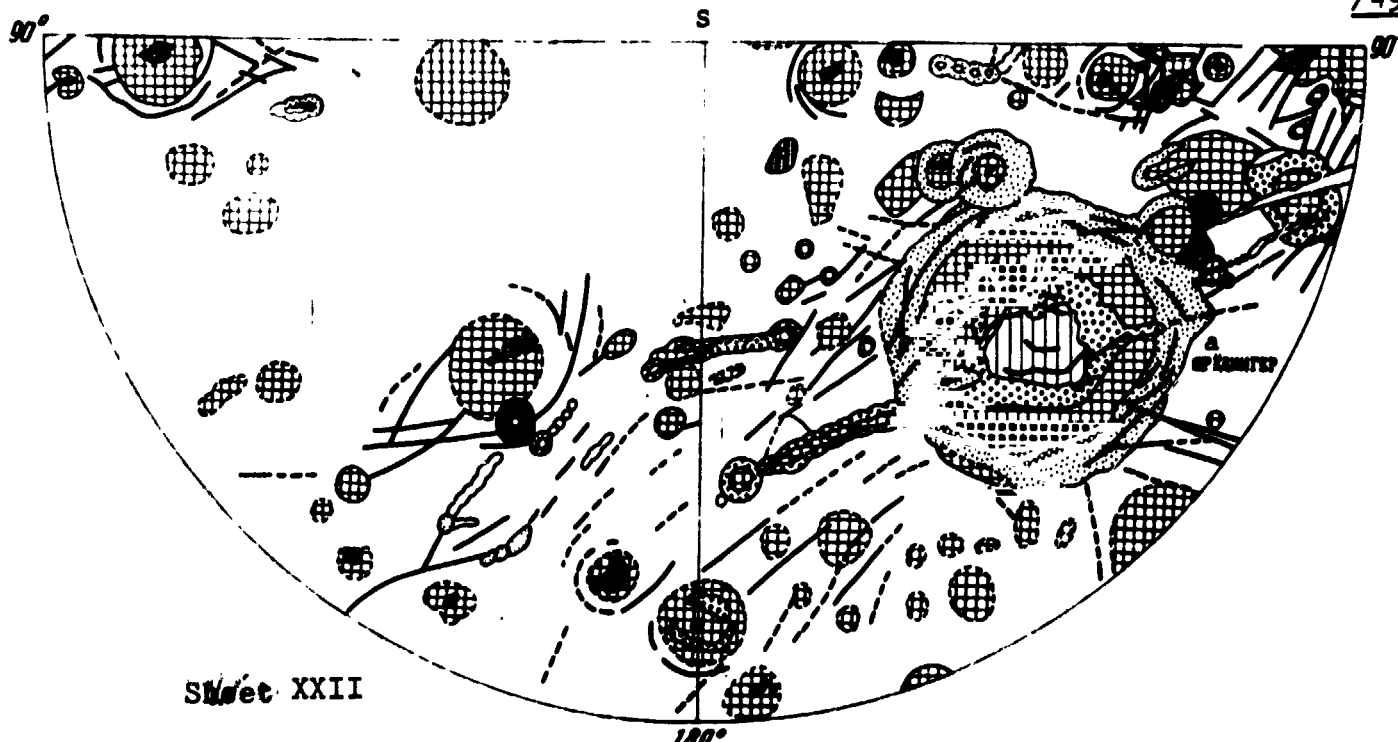
Sheet XXI

/48



Key: a. Bailly; b. Helmholtz

/49



Sheet XXII

Key: a. Schrödinger

It must be noted that many new domes (interpreted as endogenous forms) are shown in detailed geological mapping on a scale of 1:1,000,000 (Schmitt et al., 1967; Milton, 1968; Wilhelms, 1968; Schaber, 1969; and others).

Central Volcanoes

Earlier, when compiling geological and morphological maps at 1:1,000,000 ("Problems of geology of the moon," 1969), we accepted several initial positions. One of them was that the distribution of knolls, peaks and ranges in the maria were protrusions of the antemare substratum, unsubmerged remains of the mare bottom. These knolls, which were found on rugged highland regions, were not shown during mapping as special formation and were joined to the surrounding highland complexes. Individual knolls were not shown on crater walls, and the central peaks were shown by one symbol, irrespective of their position and form.

However, when studying telescopic photographs, it was noticed that among ridged and furrowed structures there frequently were isometric knolls, whose rocks distinctly overlapped the rock of neighboring areas. The same knolls were seen on crater walls. With photographs from Orbiter, it was possible to show cases of overlap over relatively even ground. Finally, the study of material on meteorite impacts convinced the author that if a single, strictly central knoll of a crater could not be an impact one, a complex central peak, a peak with a craterlet or a peak displaced from the center could be not impact, and the appearance of them was linked with volcanism. The author first attempted to describe these structures in an article, "Volcanic crests on the Moon" (Sukharov, 1969 a). At approximately the same time works appeared that showed that there were small volcano-like structures in lunar craters (Hartmann, 1968; McCall, 1968; Novikov, 1969). /27

At the present time, the existence of central volcanoes on the Moon is not disputed in principle, but their forms and distribution have been studied little. /50

Formations, referred to here as central volcanoes, are linked to domes with transitional variations; sometimes, it is not clear whether to call a certain structure a dome or a volcano. Normally, volcanoes are higher than domes, steeper, often have summit craterlets, and show signs of overlap onto neighboring structures.

On the map, they are shown as confirmed and probable. The latter are distinct in that they have poorly expressed signs of volcanism: the angular form suggests the knolls' tectonic origin; there is no summit craterlet; and no clear signs of superposition of the knoll rocks onto the adjoining area. Among reliable /51

volcanoes, the following varieties can be shown (not so much in form, as in position).

Volcanoes on Rugged Terrain

Their main feature is the overlapping of adjoining areas by rock from the volcanic knoll. If subparallel ranges and channels are developed on the terrain, they go as far as the volcano, disappear, and then continue from the base of it on the other side, without changing their general direction. For example, there is a volcano of this type near the crater Airy (18°S latitude, 5°W longitude) and a volcano between Lade and Dollond (4°S latitude, 12°E longitude). Their heights are 1 and 0.6 km, dimensions 17 x 28 and 15 x 35 km, respectively, and on their summits are single craterlets with diameters of 5 and 7 km; the major axes of both knolls are oriented at an angle of 20-30° with respect to the predominant linearity (fault direction).¹

52

In other cases, isolated volcanoes overlap individual cracks (Capella M; a structure at 5°S latitude, 38°E longitude) or a small range relief in the vicinity of large craters (Figs. 7 and 8).

Often, signs of superposition are not detected owing to the poor photography angle or owing to the small scale; however, the presence of a single hill with a summit craterlet in an area where the knolls are small can scarcely be interpreted by the impact hypothesis; these hills are probably volcanoes (for example, 117°E longitude, 48° and 52°S latitude; or 23°S latitude, 164°W longitude).

It is possible that some of them are the remains of the old foundation, rising above the surface of old maria with a rugged surface; in this case, the number of central volcanoes on the Moon is somewhat reduced, but the area of old maria is increased accordingly.

Volcanoes on the Cordilleras of Maria

Earlier it was believed that the cordilleras were composed either of ejecta from maria or of elevated rocks of the substratum. However, after the flights of Ranger spacecraft, it was suggested that some of the hills making up the cordilleras were in fact volcanoes (Ranger 7, 1965). In fact, the position and form of some elevations in the cordilleras of Mare Imbrium, Mare Crisium and

¹ Here and later, only some examples of the structures described are shown, since they are shown on the map (see Fig. 6).



Fig. 7. Crater walls of Bonpland (a), Parry (b) and Fra Mauro (c). Volcanoes are visible where the wall of Bonpland is intersected by a narrow graben; part of the graben is covered with flows or pyroclastic material; the frame width is 35 km. Symbols for interpreting the diagram: 1. crater wall; 2. volcano; 3. volcanic craterlets; 4. wall crests; 5. faults; 6. crater floors; 7. flows.

Mare Orientale do not coincide with the tectonics of these regions, and traces of their superposition onto the adjoining area are seen on their rims. In the Alpine cordillera, caldera-shaped troughs, large craterlets, and craters open on one side are visible on the tops of these elevations (see Fig. 8). The slopes of the hills are frequently flatter than the neighboring area, which is furrowed with cracks and ranges, that is, they are younger. It is 53 true that this smoothing-out was the result of talus creep or was caused by the angle at which the slopes were illuminated.

Volcanoes on Maria

It is practically impossible to reliably determine the inter-relationship between rocks projecting into a mare and rocks of this mare without detailed photographs. Small knolls, which differ in telescopic photographs, can be ejecta from craters, the remains of the substratum or volcanoes. But it is often possible to distinguish signs of superposition on areas covered by large-scale photographs. Thus, in an area near the equator between 20-40°W longitude, groups of circular knolls are visible, the surface of 54

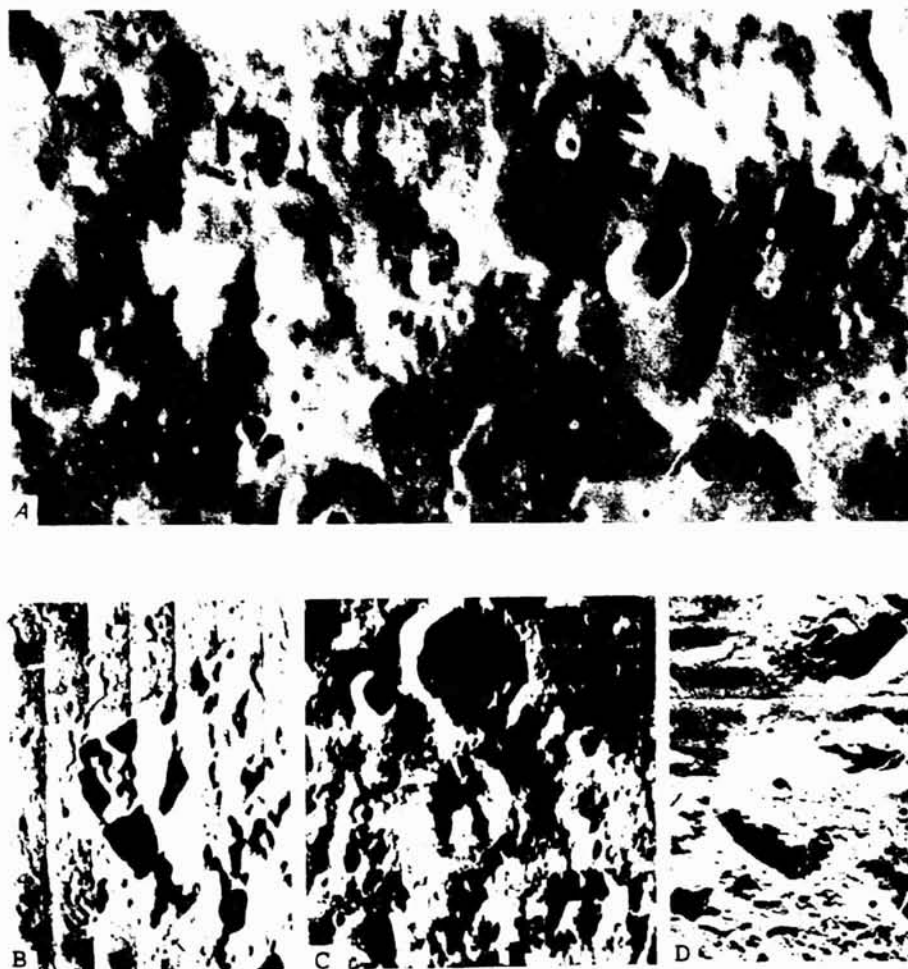


Fig. 8. Volcanoes on highlands. A. Two volcanoes on the far side of the Moon; old craters partially buried under volcanic material; frame width approximately 180 km. B. A conoidal hill (35 x 42 km) with several summit craterlets, probably of volcanic origin (Alps). C. In the center, a volcano with a lateral crater, base diameter 25 km; in the upper part of the frame, there is the crater Palmieri, the southwest wall of which is also overlapped by a small volcano. D. A dome-shaped volcano on the northwest edge of Mare Imbrium, diameter 25 km.

which is more even and lighter than the surrounding mare. The bottoms of the knolls are surrounded by characteristic ridges, similar to those of the Flamsteed P Ring. The fact that similar ridges are only seen in some knolls and crests does not simply mean that they were formed by debris. It would be interesting to

compare them with debris trains formed when extrusive domes grow as glowing ash issues from them. However, present-day extrusions on Earth are not formed on an even surface, but in the craters of volcanoes and on their slopes, and, apparently, their trains are quickly transformed by exogenous processes. When reconstructing paleoextrusions near their bases, eruptive breccias normally are seen (Koptev-Dvornikov et al., 1967), but it is not known how these breccias are expressed morphologically. In any case the lunar knolls of which we are speaking are similar to extrusions in size, form and overlapping of maria rock (that is, they are not substratum remains) and differ from those formations which are thought to be ejecta from large basins.



Volcanoes are sometimes linked with mare ridges, that is, dikes and sills (Piton, a volcano at 1°N latitude, 36°W longitude), but there are few of these examples (Fig. 9).

In cases when there are only telescopic photographs of isolated hills, their volcanic origin can be assumed by the form -- a hill in the Teneriffe group with a central subsidence and a craterlet, Pico (Herring, 1967), or, according to position -- for example, in the center of a ghost cirque.

Fig. 9. A volcano (2 x 3 km), overlapping the mare ridge in Oceanus Procellarum. Symbols are shown in Fig. 7.

The Central Peaks of Craters

Among craters on Earth with central peaks, there are none for which the meteoritic origin has been definitely proved (see above); however, the reverse has not been proved, that is, the endogenous nature of all central peaks. Therefore, the question remains open and,

if a single hill is exactly in the center of a lunar crater and if it does not overlap structures of adjacent areas and has no summit craterlets, in this case, it can only be assumed to be a volcano. A central peak can only be volcanic if it has one of the following features (Fig. 10):

a) a peak is displaced from the center of the crater; statistics show that the direction of displacement is not random, but is generally linked with the tectonics of the region (Chapman, Fielder, 1964);

b) a peak consists of several cones or knolls which are either separated or whose edges merge (the Copernicus and Humboldt craters);

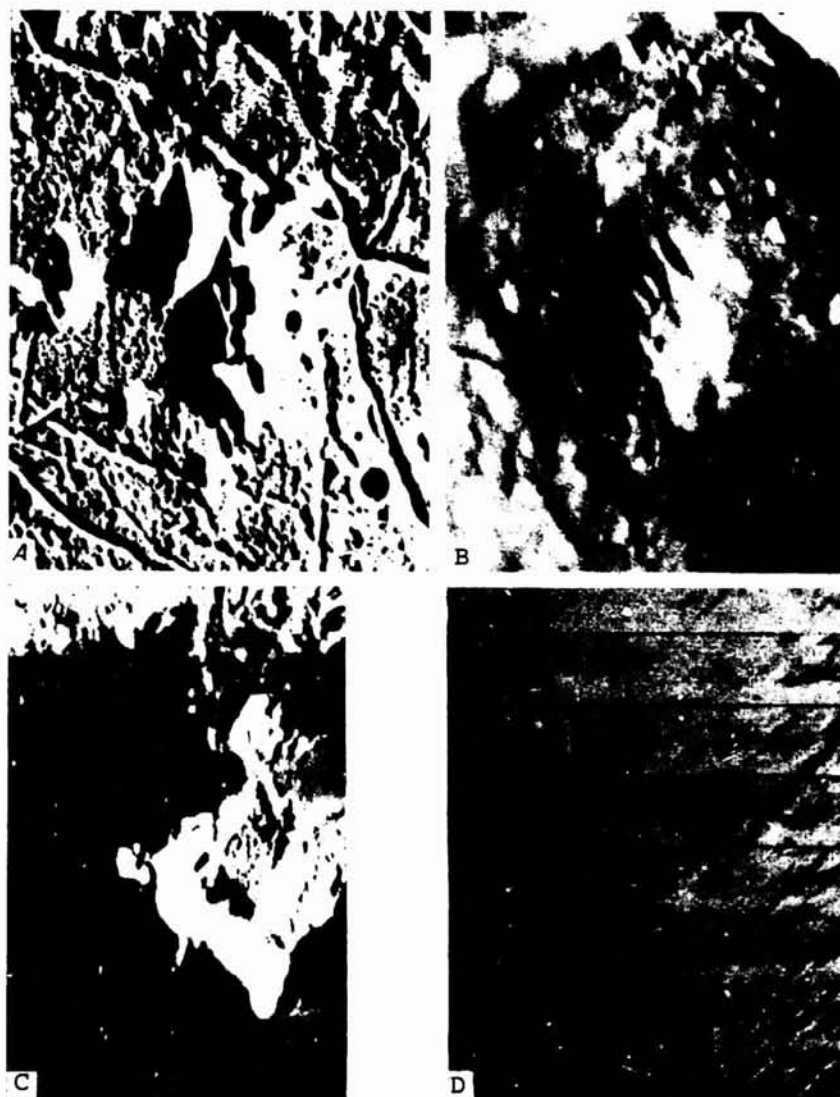


Fig. 10. Central peaks of craters. A. Gassendi; a complex central peak in the form of a crescent, in places overlapping bottom cracks and in others dissected by these cracks; frame width 50 km. B. A central peak with channeled slopes; these slopes are seen in some highland volcanoes; diameter 15 km; the center of the far side. C. The central platform of the Tsiolkovsky crater; a caldera-shaped subsidence is visible, filled with lava; frame width 60 km. D. A 5-km dike (?) in the Messier crater.

c) a craterlet or several craterlets are visible on the summit of the peak (Gassendi, Pythagorus, Keeler); in the largest craters, a large depression in the center of the peak is sometimes

seen instead of a craterlet, and this creates a central platform with a summit caldera-shaped basin (Tsiolkovsky);

d) the peak material overlaps adjoining areas (Petavius, Copernicus);

e) the peak is elongated, sometimes becoming a central crest, reaching the crater wall or even joining a neighboring crater (Schiller, Hedin, Bays Bellot).

Volcanoes on the Crater Floors

/55

They are smaller than central peaks (up to hundreds and even tens of meters in diameter). Therefore, they are rarely seen through telescopes, but are quite visible on the Orbiter photographs (Fig. 11). Normally, they are distributed chaotically over the flat bottom, forming a knoll-channeled relief with craterlets and cracks (Aristarchus, Tycho), or are grouped together, only occupying part of the bottom (Keeler, Heaviside, Copernicus). Small volcanoes such as these and their similarity to terrestrial cinder cones were noted by W. K. Hartmann (1968), V. V. Novikov (1969) and others.

Due to the mapping scale and lack of material, it was not possible to show these volcanoes individually; sometimes it is difficult to distinguish them from the irregularities of the lava field at the bottom of the crater. Therefore, they are shown on the map as volcanic regions.

Volcanoes on Crater Walls

/56

Until recently, structures of this type were rarely mentioned in the literature (Moor, 1966b), although some of them show up well on telescopic photographs (Sukhanov, 1969a). Attention was devoted to them after Ranger and Orbiter flights (Firsoff, 1967a,b; Strom, Fielder, 1968, 1970; McCauley, 1968; and others). Study of photographs taken by these vehicles showed that the positive volcanogenic forms are characteristic of many crater walls.

Volcanoes on crater walls can be well defined when they are superimposed onto a distinct crest of the wall: a crest in some parts cannot be traced, and, instead of it, a conoidal elevation appears, sometimes with a summit craterlet or an accumulation of some material with an uneven surface (Figs. 12 and 13). The boundaries of these elevations can be seen quite clearly. Sometimes they overlap a small part of the crest and are separated from it (Gambart; 23°N latitude, 90°W longitude); more often they are similar in size to central peaks (Wolf, Krylov), and sometimes they completely overlap the wall on which they are situated to the foot



Fig. 11. Volcanic forms on the floor of the crater Copernicus. A. The northern part of the floor; above, the foot of the wall, below, to the right, a central peak; the distance between the wall and the peak is about 30 km. B-D. Enlarged sections of the first photograph. The light is from the right.

(Crüger, a knoll 50 km east of Apianus). The volcano on the northeast wall of Barrow is very effective: it is clearly superimposed on the crest of the wall, elongated perpendicular to the wall, and there is a chain of merged craterlets on its summit along the major axis. The volcano is in the northeast fault zone passing through W. Bond and Barrow: on the southwest wall of Barrow, this fault appears as a crater and channel, and on the rim of W. Bond there is a volcanic trench (Fig. 14).

/57



Fig. 12. Volcanoes on crater walls. A. A section north of the crater Olbers: a. an 8-km volcano on the crest of the wall of a 20-km crater; b. a 20-km volcano overlaps a half-submerged crater with a diameter of 30 km; the frame width is approximately 80 km. B. Fractures inside the crater Struve: volcanoes appear where crater walls are intersected by fractures (the distance between the upper and lower craters is approximately 90 km). C. Prosper Henry, diameter 40 km: a sharp crest overlapped by volcanic accumulations. D. Anaxagorus, diameter 50 km: volcanic accumulation on the wall merge with the central crest.

Apparently, some sections of crater walls consist completely or partially of small merged volcanoes (Alphonsus, Ptolemaeus, Olbers).

Besides volcanoes on the walls, there are lava lakes and flows which move down from the wall to the crater and outwards (Fig. 15). The lakes are found either on the depressed crest of the wall, in local depressions (Alphonsus, Tycho), or on the internal slope of the wall, in the rear parts of concentric terraces (Copernicus, Aristarchus). These lakes are also seen on the external slopes, where they overlap flowing "ejecta" structures. These lakes should not be considered lava, but fragmental accumulations, since their craterlet density indicates their age to be at least tens and hundreds of millions of years, and not modern, whereas a fragmental cover should be formed now, sliding from the

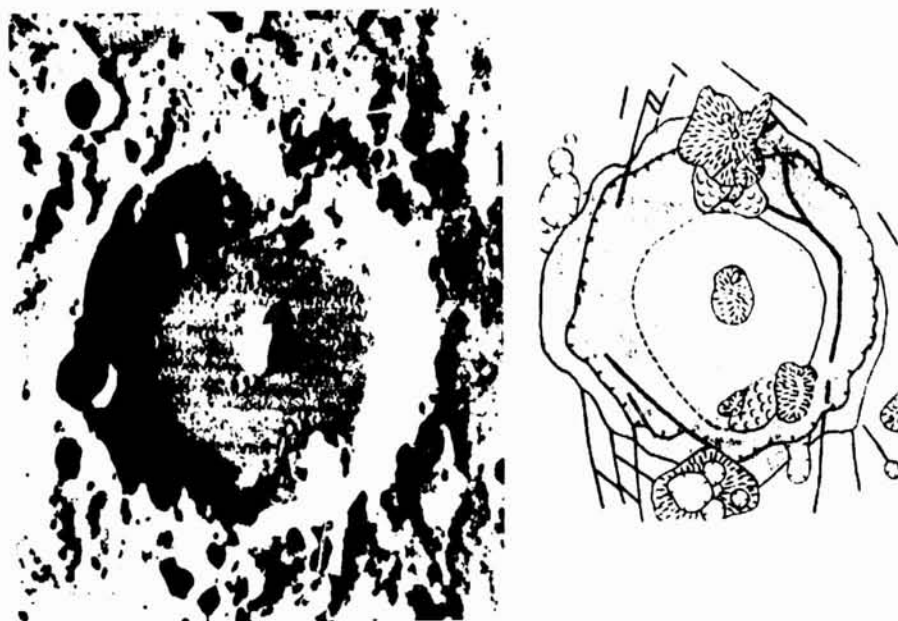


Fig. 13. The crater Krylov. On the walls are shown volcanoes with flows leaving them; narrow walls; to the east, the area adjacent to the wall crest is not overlapped by "ejecta." The crater diameter is 55 km. Symbols are shown on Fig. 7.

slopes and filling the craterlets; moreover, alluvial deposits such as these should be seen on the contacts of the floor with the wall, but the morphology of these areas often differs from the morphology of lakes. In places one can see that the lake flows through a breach in the surrounding benches, and the lava flow is directed down the slope from this breach; such a flow from the marginal walls on the north side of Copernicus can be seen very well. /58

In places, slides of material with a coarse, uneven surface extend from the volcanoes on the crest of the wall to the floor of the crater (Keeler, Pythagorus, Anaxagorus). It is difficult to say what this is: streams of viscous lava or volcanism zones intersecting the wall. Probably, some of these formations do not differ morphologically from the remaining slopes of the wall and are only visible since they are on the north and south rims of the crater, that is, are indirectly illuminated (whereas the west and east sides are in shadow or are directly illuminated); then it would be wrong to show them. But this only refers to some slides. /59

Finally, on the external slopes there are massive flows with a coarse surface, later overlapping each other (Strom, Fielder, 1968) and light furrowed covers (Gorshkov et al., 1970).

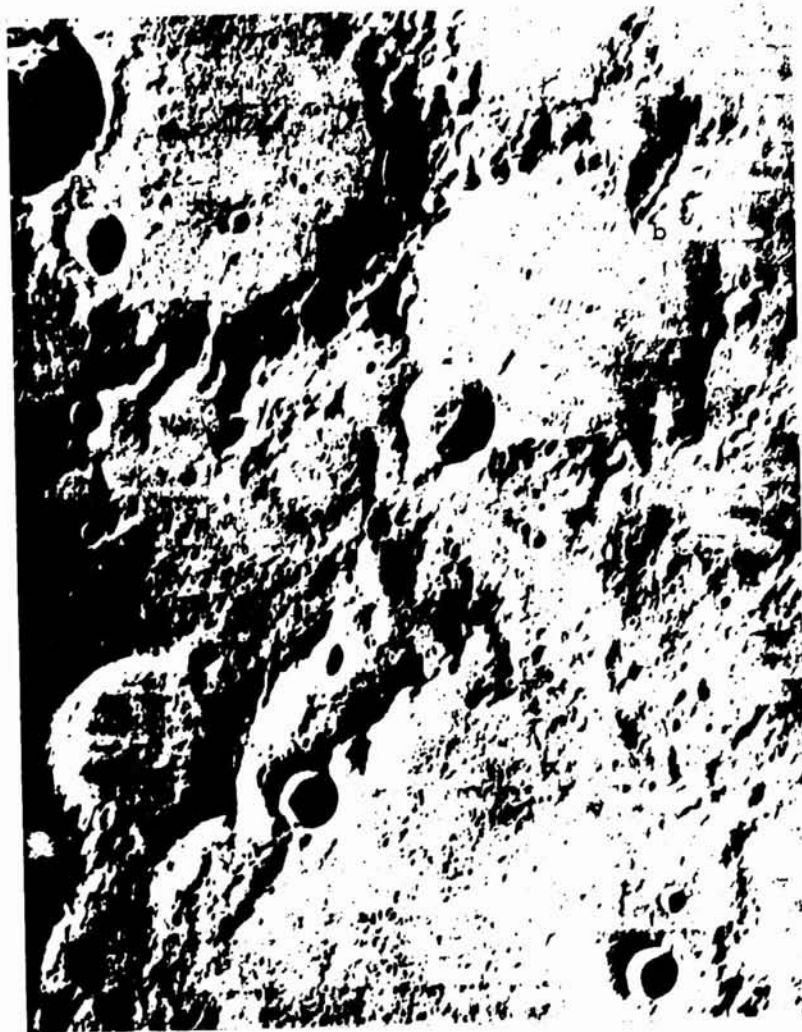


Fig. 14. The highland north of Mare Frigoris. Above to the right, the crater Barrow (a). A disruptive disturbance zone passes through the whole frame from the lower left corner to the top right; where it intersects with the northeast wall of Barrow is a volcano (b), size 25 x 40 km; below, to the left along the fault, there is a volcanic-tectonic depression. Frame width 250 km.

More will be said later of ring ridges consisting completely of volcanoes and extrusions.

As in the case of individual volcanoes, volcanoes which have not been superimposed are not positive.

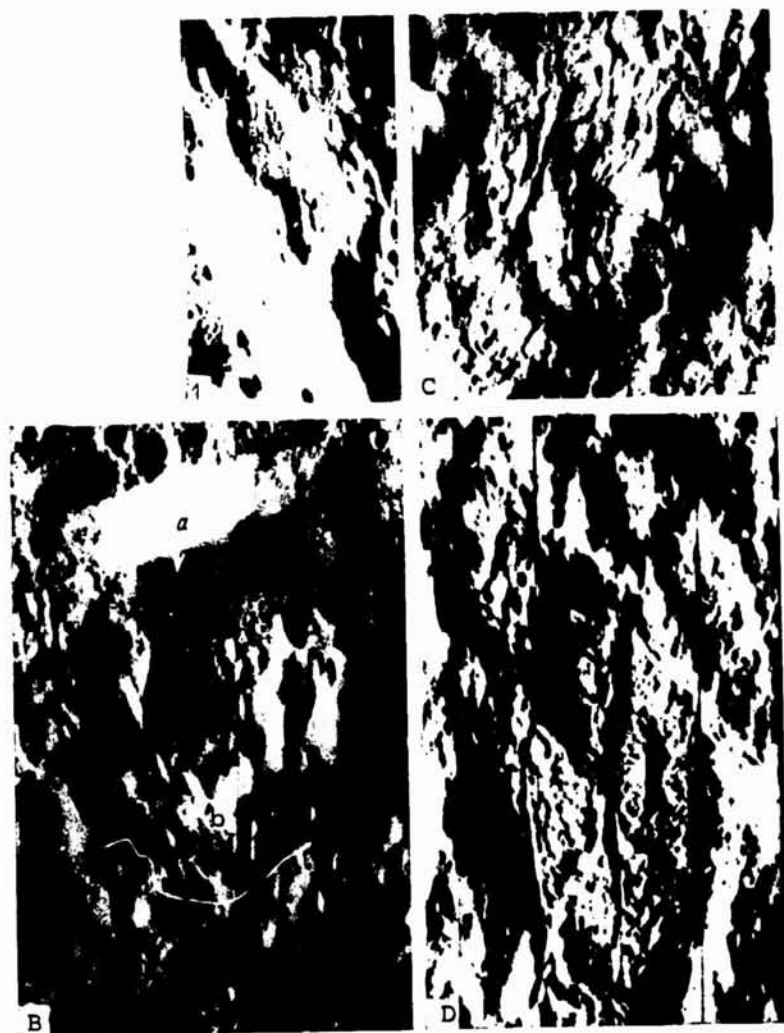


Fig. 15. Lava on crater wall. A. A lava lake approximately 30 km long on the crest of the Alphonsus crater wall. B. The crater wall of Copernicus, frame width approximately 15 km: in the rear section of the terrace can be seen a lava lake (a); there are flows running down from it (b). C. A flow on the external slope of the Aristarchus crater; frame width approximately 2 km. D. Flows on the external slopes of the Tycho crater; length of flows 3-5 km.

Dikes and Volcanic Crests

/60

Often volcanoes in a mare or on the highlands are elongated, and sometimes become volcanogenic crests. Normally, the volcanic nature of these crests can only be determined where there is an interrelationship of them with ring ridges. These crests were described by the author in an article, "Volcanic ridges on the

Moon" (Sukhanov, 1969a). These ridges either intersect the ring ridges of craters (Franz, Lyell, Sabine), or merge with open crescent ring ridges (Lade S, Parry M, Silberschlag S, Birmingham). In the first case, the ridge is a superimposed formation, and its link with the tectonics of the area and traces of shifts along the ridge leave no doubt as to its volcanic nature. In the second case, the close link of a rectilinear ridge with a half-ring ridge to which the ridge is attached at a tangent, shows their syn-genetic nature and can hardly be explained by the impact theory.

It is difficult to distinguish volcanic crests from tectonic (slants, horsts) and from ridges fringing volcanic furrows (closely merging chains of small craters, whose cumulative sides meet in long strips); when combining volcanic trenches with tectonic displacements, the picture is somewhat confused. According to some signs (structure details, the predominant orientation, etc.), there ought to be more volcanic crests that were shown in the vicinity of circular maria (Orientale, Imbrium, and Crisium).

The mare ridges were not specifically examined here. It must be noted that the concept of the folded nature of these walls was not confirmed when studying large-scale photographs. Individual ridges, making up the mare ridges, sometimes intersect other, earlier ridges, and with them form two or three age generations. The diagram of ridges in plan is similar to that of fault systems (a linear-imbricate arrangement, cleavage of the "horse's tail" type, and the tracing of subparallel fault systems running from the highland to the mare). The ridge profile is like that of flows, dikes and fissured extrusions. There is sometimes clarification along the swells, and small volcanoes are seen. The author is of the same opinion as those investigators who believe that mare ridges are dikes, sills and laccolith-shaped bodies (Ranger 7, 1965; Ranger 8 and Ranger 9, 1966). In this respect, instances of arc and ring position of ridges which trace the crests of submerged craters deserve special attention.

Volcanic Regions

The overwhelming majority of areas of effusions (old and young) is formed morphologically by monotonic lava covers. However, on some areas the mare surface is covered with numerous knolls, craterlets, chains of craterlets, cracks, furrows and holes. These areas fall into two types. In the first, knolls and hills of different heights, often with rectilinear boundaries and broken by faults, rise above the mare surface; there are fragments of half-ring (submerged) crater walls. Obviously, these regions are part of the highland covered by a shallow mare cover with relicts of highland relief.

In the second case, small knolls have smoothed-out features, similar dimensions and differ little in height, but their tops

/61

form a level surface, which is not characteristic of steptoes. The direction of craterlet chains of some regions shows the link with the tectonics of the surrounding area, since these craterlets cannot be secondary impact ones. Therefore, it must be admitted that the relief of these regions is caused to a considerable extent by postmare volcanism, which distributed volcanic craterlets and cinder cones over the area; obviously, the nature of volcanism here is different from that under normal conditions of effusion areas.

Examples of these are the Aristarchus plateau, the plateau north of Mare Imbrium, and ring basins which fringe Mare Orientale. The structures of these and other areas similar to them are so small that they are not visible on the map scale and are not shown as individual volcanic regions (Fig. 16).

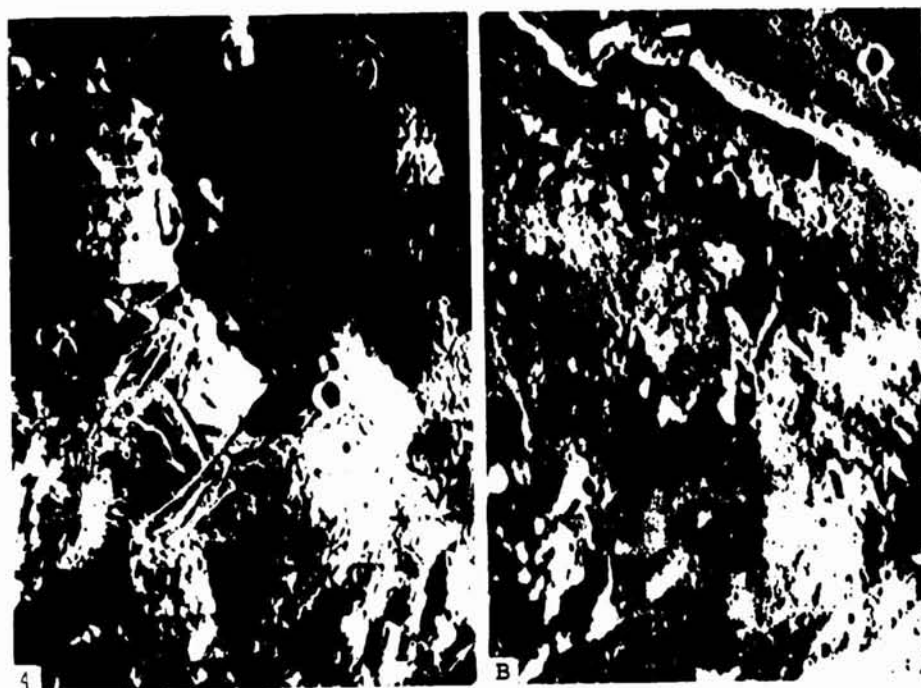


Fig. 16. Volcanic regions. A. The southwest part of Mare Orientale, frame width 130 km. The areas where the lava shield with few cracks changes to dome-shaped elevations with a fissured hummocky and furrowed surface; arrows show several steeper knolls (volcanoes?). B. The Aristarchus plateau, frame width 50 km. Areas of different luminosity are visible and a different degree of leveling (flows of various ages), and there are many smoothed-out knolls (cinder cones). Schröter's Valley (above), apparently, is a separation.

Volcanogenic Craters

Inconsistencies between the meteoritic and volcanic hypotheses lead mainly to the question of craters; therefore, they should be examined very carefully. In this work, craters measuring from 5-10 to 100-120 km are examined. Smaller craters are not shown owing to the map scale, and, moreover, they are poorly visible on the medium-scale photographs available. Larger craters and thalassoids are characterized by several specific structural features as, apparently, are forms becoming ring maria and, therefore, are also not examined. /62

The endogenous origin of a crater is determined by its position with respect to other formations on adjoining territory, the planform of the crater walls and their surfaces, and on the internal crater structure. Table 2 shows these signs; they are examined in more detail below.

1. The distribution of craters in chains, pairs or clusters.

Small craters -- craterlets with a diameter of several kilometers -- are normally found in chains. The endogenous chains were those whose direction was subject to the direction of faults of the surrounding area, and those which, by their own rectilinearity and size of craters in them, are shown in the area, that is, the area around a chain covered by craterlets, smaller than the chain craters; craterlets, equal in size to chain craters, are spread randomly, and the difference between them is many times greater than that between chain craters (Fig. 17). Therefore, only the most positive cases have been determined, and many endogenous chains, which become lost among the large number of impact craters, are not accounted for. In particular, there could be endogenous formations around flow and ray craters; however, according to the photographs available, it is almost impossible to distinguish them from secondary impact forms. /63

The tectonic conditionality is seen best in the following cases: a) a chain of oval craterlets very close to each other with a diameter of 1-3 km between 33 and 35°N latitude and 43°W longitude; to the south this chain is directly transformed into a mare ridge, and the remainder of it can be traced in the gaps between the chain of craterlets; the craterlets are surrounded by relatively small ridges, and it appears that they occurred not as the result of ejection, but when the crest of this ridge subsided; b) craters of the Hyginus Rille. The latter is sometimes interpreted as a secondary structure, that is, a fissure which occurred after several secondary fragments had fallen, creating a chain of craterlets. However, the Hyginus Rille is parallel to the Ariadaeus Rille, and is south of a tectonic scarp (the edge of an old mare); it is filled with lava and plugged by several volcanoes, and craterlets along the shore are younger than its lava floor. The rims of craterlets are slightly elevated, which indicates /64

TABLE 2. CRITERIA INDICATING VOLCANIC CRATERS

Volcanogenic signs	Typical craters
1. Arrangement of craters of similar structure in chains, pairs or clusters when there are no craters of the same size and similar structure in the surrounding area.	The Davy chain at 33-35°N latitude, 43°W longitude, Rheita E, Sabine and Ritter, Wright and Shaler, a group of craters in the Aitken cirque, Langrenus B, F, K, a group of craters south of Inghirami
2. Craters of similar structure and of a certain period for specific areas when they are few of them in other areas	Arrangement of concentric craters on the edges of maria.
3. Structural links between craters adjoining or next to each other (the transition of structure elements of one crater in the structure elements of another); the mutual intersection of crater walls.	Ptolemaeus-Walter chain, Olbers-Hedin, Watt-Steinheil, Main-Challis, Spinoza.
4. Concentric structures inside the craters (with a diameter greater than 10-20 km)	Posidonius, Gassendi, Vitello, Lavoisier, Damoiseau, Hansteen, Pitatus.
5. Sharply polygonal, very elongated, scalloped crater walls.	Boscovich P, Réaumur E, Schiller, Van de Graaf, a crater in the Barbier cirque.
6. The anomalous width of a crater: a narrow wall in a large crater and vice versa; the absence of a wall (the surrounding area is joined to the crater's internal slope)	Krylov, Gambart, Kopf, a structure at 107°E longitude, 7°N latitude.
7. The smooth external slopes of walls relative to young craters.	Delambre, Sabine, a crater at 36.5°N latitude, 73°W longitude, a twin at 5° and 6°S latitude, 145°E longitude, Wright.



Fig. 17. Crater chains. A. A merging chain on the far side of the Moon, frame width 80 km. B. a volcanic trench and a chain of craters near Copernicus; the length of the structure is 50 km. C. Three craters (8, 15 and 15 km) north of Ritter. The nearest craters of the same size are 40-50 km away, and, at this distance, there are only small craterlets -- some of which reach a size of 1-3 km. D. A crater chain which is a continuation of the mare ridge, partly passing through its crest; the length of the chain is approximately 50 km; Oceanus Procellarum. E. A chain of craterlets, 1-3 km in size in the Davy crater.

explosive activity; c) a chain, stretching from the northeast side of Ptolemaeus to Albategnius; here, the closely arranged polygonal craterlets have distinctly accumulative rims, and the direction of the chain is caused by the tectonics of the area.

An example of an isolated chain, not linked with tectonics, is a 50-km, slightly curved series of craterlets east of Davy with a diameter of 1-3 km; the form of each of them is distinct from any one of the numerous craters thought to be impact ones, but, as seen on a photograph, there are no craters of the same size in the vicinity.

Craters in a chain often merge together and form a crater furrow (volcanic trench) as, for example, the Rheita Valley and Rheita E. There are many of them between Mare Nubium and Mare Nectaris. Among them there are many varieties which are close to grabens in features (aligned rims, trough-shaped bottoms), so that it is difficult to draw a boundary between those and others (a furrow, cutting Gylde, a ditch on the wall of Julius Caesar). When the photograph has insufficient detail, one can accept the fault -- the fissure or graben with collapsed sides, which causes the ripple of the sides in plan -- as a chain; therefore, doubtful cases of this type have not been mapped. Finally, merged chains become concentric structures of crater walls, but again they are only visible on rare occasions, since it is difficult to distinguish them from the scarps of warped terraces.

The chains also form several large cirques (Ptolemaeus-Walter, Hecataeus-Humboldt), but, in these cases, the structural links of these cirques determine the endogenous nature; chains of cirques, not showing these links, can be shown by random combinations (Wiener-Plasket, Pauli-Purkinje). Among craters in isolated pairs, the only endogenous ones are those which are structurally interrelated or have an identical structure, which is different from that of the surrounding craters; therefore, this is not true of twin craterlets, which are always similar to craterlets of the adjacent area and can be completely formed by impact. Most typical are Wright and Schaler (Mare Orientale), which are craters of equal size and identical structure with contiguous rims, and around which there are only small craterlets at a distance of five of their diameters -- the largest of these has a diameter half that of Wright. Another example is Sabine and Ritter, contiguous craters with concentric structures; around them there are no craters of similar structure.

The craters are also grouped according to the similarity of their internal structure and the fact that there are no craters of similar size and structure in the area (Fig. 18). Thus, in the Aitken cirque, there are five craters close together with low, narrow walls of similar size, in three of them the floor is filled with adjoining domes, in the fourth, there is one central dome, and all the craters around this group are much smaller. There is another group south of Inghirami (approximately 51°S latitude, 68°W longitude) on an old mare surface: four craters in this group almost touch, their dimensions are 20-30 km, and the nearest craters of the same size are 100-140 km away, and the remaining



Fig. 18. A concentration of craters in the Aitken cirque with domes on the floors and low, flattened walls. The wall of crater a is hardly discernible, and crater b has no domes on the floor, but the morphological similarity and similar size of all five craters indicates the generality of origin. The craters are on the lava floor of a large cirque; on the right, at the edge of the floor, there is a structure like a mare ridge. Frame width is 35 km.

craters in the gap are either smaller or much larger than the craters of this "cluster." Craters of the "cluster" are similar to each other in structure and differ from the general mass of craters surrounding Mare Orientale, to whose zone of influence they belong: in plan, they consist, as it were, of several superimposed and slightly displaced circles, the external slopes are smooth and gently sloping, the internal ones very steep, and the floor is partially filled with dome-shaped bulges.

Some groupings can only be shown as probable ones, for example, cirques of the Gutenberg-Goclenius-Colombo group. They have flattened, as it were, powdered walls, a similar profile, age and dimensions, but some differences in age show that they were not formed from one meteorite swarm. However, the surrounding area is submerged, and there is a wide belt of faults with shifted displacements, so that it is quite probable that the smallest craters of this area are overlapped and dislocated.

Finally, there are very vague regularities of distribution, such as the Langrenus-Vendelinus-Petavius-Furnerius line, or the identically positioned Fracastorius and Piccolomini, with the same dimensions on the north closure of the Mare Nectaris cordilleras. It is possible that the arrangement of these craters /66

is random, and that, by finding a regularity here, we are indulging in wishful thinking; this question can only be solved by statistical processing of the material on the frequency and distribution of craters of similar size.

2. The fact that craters of one type are confined to certain zones. This law is only clearly expressed for concentric craters, the majority of which are on the edges of maria and in regions near them. In other cases, this link is only assumed, but cannot be shown as being reliable: for example, a strip of craters with similar dimensions, Aliacensis-Almanon, passing over a poorly marked bend of the surface, to the northeast of which the area is intensively submerged.

3. The structural links of craters. These are seen quite seldom: normally, one of two neighboring craters simply overlaps the other. Therefore, it must be accepted that craters, in which the structures of one are continued by structures of the other, were not formed in a "standard" fashion; probably, these structures were formed by a prolonged endogenous process.

Structural links show up well in the Ptolemaeus-Walter chain in the pairs Olbers-Hedin, Miller-Nasireddin, and Watt-Steinheil, in the structure of the complex crater Spinoza, and in a group at 7°N latitude, 108°E longitude. They are pronounced, since the wall of one crater can cross into the central ridge of the neighboring, two craters have a direct abutting closure, or the enclosure is lowered and a single longitudinal ridge extends along the axis of the crater pairs; the walls of neighboring craters are connected by tangential faults and ridges. The walls, and the latter become the internal slopes of walls and are transformed into terrace-forming faults; sometimes a ridge which passes inside one crater branches off from the wall of another crater; the polygonal walls of some craters merge into an irregular, meshed structure. In the case of Posidonius and Chacornac, one can see that the wall of Posidonius overlaps the north wall of Chacornac, and at the same time its northern wall is not overlapped and merges at a tangent with the wall of Posidonius, which is impossible for impact origin.

As has been said, in the majority of cases, the wall of a young crater overlaps the wall of an older one. Sometimes abutting closures are lowered and submerged. But there are craters where there is no submersion, but no signs of overlap or abutting closures; it can then be concluded that this occurred almost simultaneously, or the craters took a long time to form and are probably endogenous (Vogel-Vogel A).

Examples of mutual intersection of crater walls are rare but very representative. They were first noted by P. Moor (1966b). It is true that all the examples he showed were not confirmed later, /67

and what he believed to be traces of old walls on the floors of young craters were their central peaks (Vlacq, Rosenberger). The appearance of volcanogenic (complexly formed) central peaks in small craters on the walls of large cirques is in itself interesting, but now this is not being discussed. In Figs. 19 and 20, it can be seen that there are pairs of craters, the walls of which mutually intersect each other, which is impossible when there is impact origin of both craters; at least one of them should be volcanogenic. Normally, both such craters are morphologically similar, and one can accept the volcanogenic origin of either crater (Main-Challis, Nasmyth-Phocylides).

Apart from the distinct mutual intersections, there are cases when a volcanic structure occurred where the walls of an overlapping and an overlapped crater meet (Wiener, Einthoven, a crater to the east of Parcellus). If the craters are impact ones, it is unclear why the volcano occurred at the point which is overlapped most by ejecta (the superposition of two walls) and the least fissured (on the rim of either crater); whereas the intersection of two magma-supplying ring cracks is the most suitable place for a volcano. /68

4. Concentric structures. In craters with a diameter on the order of tens and hundreds of meters, these structures, in principle, are explained by the meteoritic hypothesis (if one accepts a two-three layer model of the substratum, where the impact crater is formed). The impact origin of these craters is confirmed by the great quantity of large blocks strewn around the craters.

Concentric structures are rarely seen near craters with a diameter of not more than a few kilometers, and differ morphologically from smaller concentric forms: in essence, this is two or three craters nested on top of each other, with well-defined walls (Marth; a crater in Humboldt, between its central peak and the east wall). In a 6-km crater at 35°N latitude, 43°W longitude, between the central craterlet and the external polygonal wall, there is a half-ring of domes, obviously endogenous (Fig. 21). If these craters were formed by impact, there should be many more of them on the lunar surface among craterlets of the same size. Apparently, these craters were formed by the accumulation of pyroclastics around central vents and correspond to composite volcanoes on Earth; some concentric ridges are formed when there are several series of eruptions, differing in intensity.

The map mainly shows concentric craters with a diameter on the order of 20-100 km. Normally, their concentric structure was not formed by one wall, but by heterogeneous elements: ridges, fissures, furrows, chains of domes, and scarps (Fig. 22). The whole concentric structure can be shifted relative to the center of the crater and can adjoin the main crater wall (Posidonius, Gassendi). There are craters in which the central part of the floor is

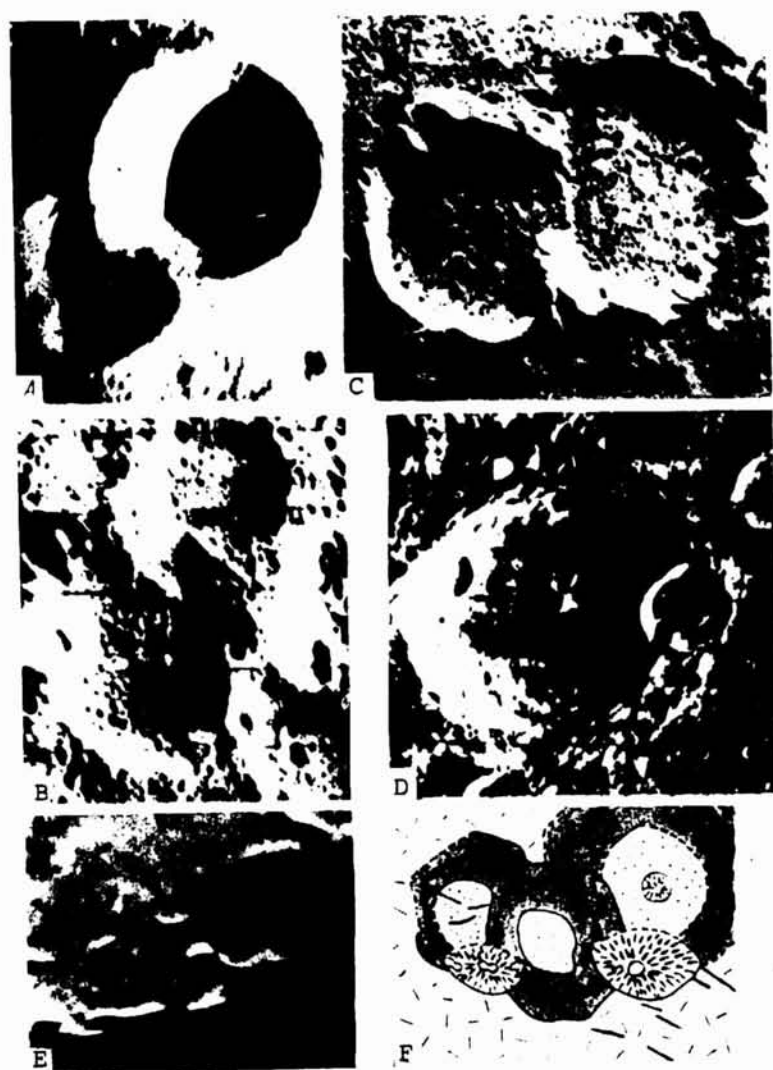


Fig. 19. Mutually intersecting craters. A. Craterlets in the Alps, diameter greater than 6 km. B. A structure east of the crater Biela, frame width 70 km. C. Main and Challis, 50 and 60 km (the north polar region). D. Biela, diameter 70 km: the crest of the eastern wall can be traced inside a smaller, but younger crater. E. Parry M, diameter 25 km; the place where the walls intersect is shown with an arrow. F. Craters between Clavius and Longomontanos, the diameter of the middle one is 30 km: the walls of the north and south craters are intersected by the walls of the middle one; at the intersection there are volcano-like elevations. The symbols are shown in Fig. 7.



Fig. 20. The Nasmyth and Phocylides cirques. The walls of one cirque intersect the walls of another, but in their turn are cut by them. Symbols shown in Fig. 7.

raised in the form of a round platform, and the protruding edges of this platform form a ring ridge (Sabine). In some craters, a belt of small concentric ranges and fissures directly adjoin the foot of the crater wall (Lavoisier) and in other are separated from the wall by a strip of mare rock (Inghirami).

/69

All this variety of structures could not have appeared as the result of identical meteoritic impacts. The endogenous origin of concentric craters is confirmed by other signs: smooth external slopes (Vitello), the extrusive origin of part of the main wall (Gassendi), structural interrelations (36°N latitude, 77°W longitude), and, mainly, the distribution of these craters along the edges of mare basins and the small number of them in other areas.

5. The form of a wall in plan. This can be a criterion of the endogenous nature of a crater when it cannot be explained by other means. Craters with polygonal outlines can be caused during the impact of meteorites (Arizona); and when secondary fragments fall with a speed not less than 4 km/sec, elongated elliptical forms occur (Baldwin, 1967).

On the other hand, a considerable number of large craters are changed by subsequent processes; their walls are often aligned by faults, distorted by displacements, the internal parts sink and become covered with lava, and this subsidence embraces the internal parts of the walls and the abutting closures of neighboring craters (Khabakov, 1949; Spurr, 1944-1950; Sukhanov, 1969a).

It should be possible to determine in some way the degree of deviation of crater form from the circular, and whether craters with a deviation above a certain value are endogenous. However,



Fig. 21. Small crater with an internal craterlet, crater coordinates 35°N latitude, 43°W longitude. The internal craterlet is circular; the external wall is somewhat polygonal, with smooth external slopes; a chain of domes is visible between the external and internal walls. Frame width 5 km.

work in this area showed (Adler, Salisbury, 1969) that for the majority of cases these deviations are mainly linked with the age of the crater and, accordingly, the degree of its dislocated nature, and not with its initial shape.

In another work (Murray, Guest, 1970) an estimate of the circular nature of lunar craters showed that that, according to this index, 85% of them are similar to meteorite and artificial explosive craters, and the remaining 17% are closer to calderas -- this 17% included all craters, the caldera origin of which was assumed using morphological information. However, these authors only used nondislocated, mainly mare craters; the question of highland craters (and this is a majority) remained open.

A similar statistical processing of highland craters could give interesting results, but it is too large to be included in this work. Therefore, the map only shows the best examples of polygonal and elongated forms (Figs. 23 and 24).

Therefore, it is impossible to explain the occurrence of extremely elongated craters such as Schiller by any impact effects. The outlines of this crater's relatively fresh walls do not give basis to suppose that it has been modified by a merged crater chain; also, in the area there are no fault systems on a scale sufficient for such a modification. The nature of the wall and its width differ little on various sides of Schiller; therefore, it could not have occurred during an oblique "plowing" impact, which would have created directed ejecta. (In general, it must be noted that directed ejecta are visible in some small elliptical secondary craters, but hardly anything similar is seen in large elongated

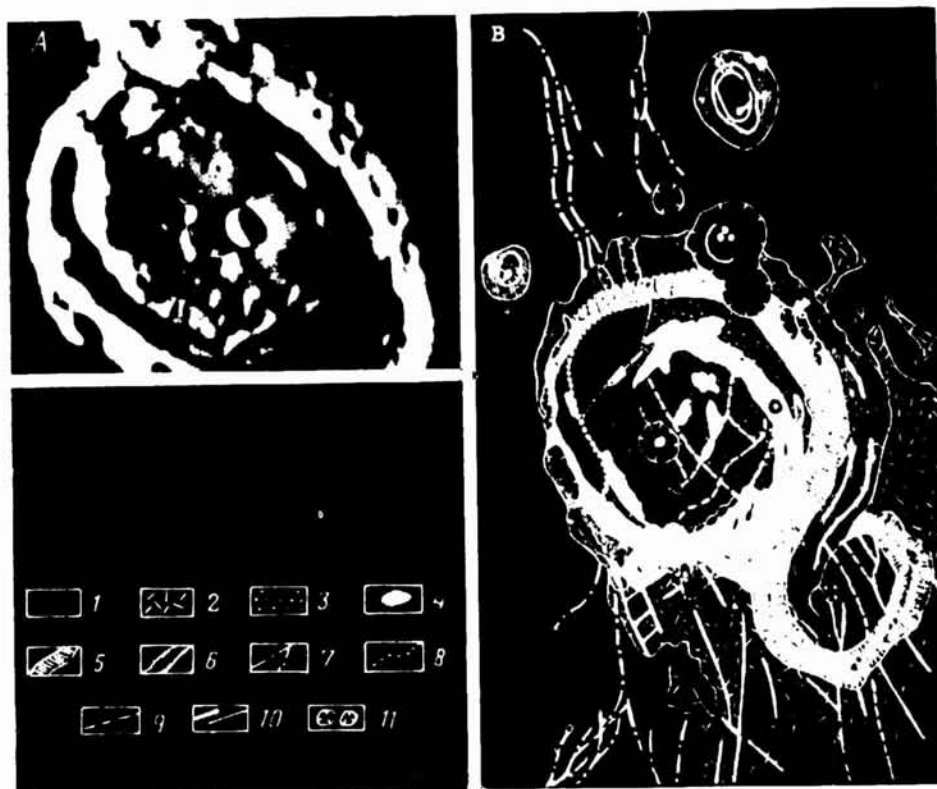


Fig. 22. Posidonium -- a crater with concentric structures (diameter 85 km). A. A telescopic photograph (with a somewhat distorted aspect). B. An interpretation diagram: 1. mare; 2. highland; 3. length of crater; 4. volcanoes; 5. ring ridges; 6. external wall zone; 7. mare ridges; 8. rilles; 9. opening fissures; 10. faults; 11. craterlets.

forms). The same can be said of Van de Graaf and its straight northeast walls.

Another elongated crater, Boscovich P, is in a subparallel fault zone, and the direction of its major axis coincides with the direction of the faults. But no ejecta or displacements could create such delicate straight walls forming a rectangle, even from an oval crater; this is not a question of oblique impact.

/70

The graben-shaped trenches with straight, subparallel, narrow walls (like the furrows on the wall of W. Bond or Baade) cannot be explained by oblique "plowing" impacts: they curve as they stretch, and include necks and individual craterlets, and there are rectilinear ridges over large areas which could not have occurred when chains of debris fell.

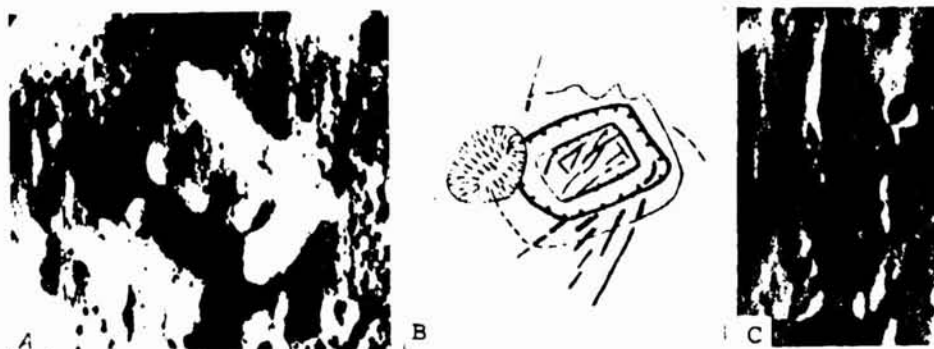


Fig. 23. Rectangular craters. A. A crater-subsidence 6 x 8 km on a highland protrusion between Mare Imbrium and Oceanus Procellarum; the walls are hardly expressed; there are three domes on the bottom. B. An interpretation of a crater 12 x 17 km in the Barbier cirque on the reverse side; the symbols are seen in Fig. 7. C. Boscovich P, a graben-shaped crater approximately 60 km in length, with narrow, interrupted walls, filled with dark mare matter.

Some crater chains in which the internal closures are sunken and submerged could be volcanic, since only subparallel walls, consisting of scarcely discernible semicurved segments can be seen over the area. Here, the ejecta (graben) and volcanism (submersion) are general for the whole furrow, which shows the deep roots of the structure.

An indication of the endogenous nature of the craters are the polygonal walls, whose rectilinear segments continue over the surrounding area in the form of ranges, faults, and the rectilinear segments of neighboring crater walls or craterlet chains (Ptolemaeus, Alphonsus, Birmingham).

In some instance, the walls of round craters are also continued at tangents by straight ridge (a small crater on the wall of Mazzini, Riccioli). Some of these "continued" crescent craters were described earlier by the author (Sukhanov, 1969a). Of course, these could be complete coincidences, especially where there is intensive submersion, where only random segments of ridges remain from densely packed, angular craters. But as a whole, crater walls which pass with interruptions into tangential ridges should be considered endogeneous, especially when there are other traces of volcanic activity.

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6. The anomalous width of a wall. In the majority of cases, the determined width of a crater wall corresponds to a crater of a certain diameter, and this coincides with the hypothesis of the meteoritic origin of a crater. But there are large craters with

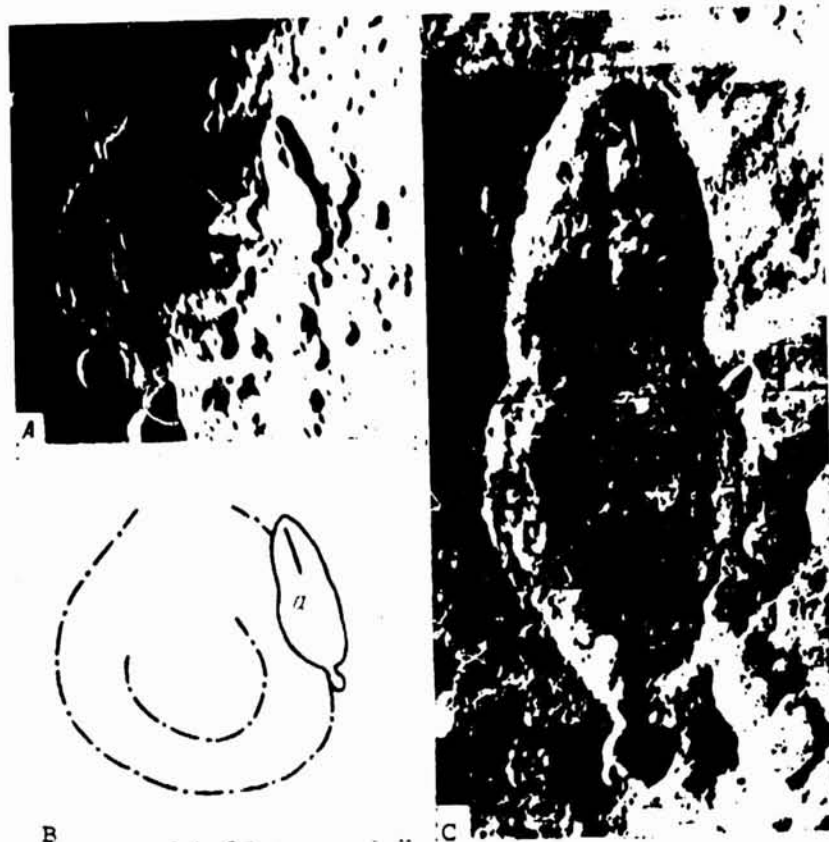


Fig. 24. The crater Schiller. A and B. The position of the crater in the thalassoid structure; continuous lines are outlines of the crater and its central dike (a), the dot-and-dash lines are crests of the thalassoid walls, C. The crater on a larger scale (100 km along the major axis); one can see well that Schiller is not formed from a series of merged craters, as would have occurred during impact origin, but is a single structure. In the north part, there is a dike, elongated along the crater's axis.

unusually narrow walls (of course, we are talking of well-preserved craters, whose walls are not overlapped by later deposits -- lava or ejecta of neighboring craters). Hence, in the 45-km Reinhold, the average width of the external slope of the wall is approximately 15 km, which is typical for this size. But in the 50-km crater at 18°S latitude, 90°W longitude, the width of the wall of the external slope is only 5-7 km (here, the material of the wall overlaps the surrounding area). Obviously, meteoritic ejection should make the width of the wall much greater.

In the crater Krylov, there is no accumulative wall whatsoever /72 on some sections: the surrounding area rises as it approaches the crater and merges with the crater's internal slope and does not overlap it; this elevation is most probably of tectonic origin. In some small craters (with a diameter of approximately 5-15 km), there is usually no elevated wall; obviously, these craters occurred due to subsidence without ejection.

On the other hand, there are some small craters on wide, gently sloping elevations which merge unnoticeably with the surrounding area, and their volume is less than that of the wall. This cannot be explained by ejection.

7. Smoothed-out external slopes of walls. There are many of these among old craters, but few of them among young craters; furthermore, photographs are normally not detailed enough to determine the wall's fine structure. Probably, in old craters this smoothing-out is due to the prolonged reworking of the initial, uneven surface; this is especially true of small-diameter craters, where there is little range of the primary slope relief. But in young craters, it is primary and shows the endogenous nature of the crater. In all craters assumed to be of impact origin (where there are elongated rays and secondary craterlets), the external slopes have a stream-like, wrinkled and furrowed or dune relief, and sometimes there are individual blocks, tens of meters in diameter, strewn chaotically over the wall. The fact that there is no such relief on the slopes of a wall indicates that the crater was formed in another way (non-impact). /73

Two small craters can be taken as an examples: Mösting C, diameter 3.8 km, with a halo of light rays and dune relief of the walls, and Copernicus H, diameter 4.6 km, with a dark aureole and smooth slopes. The first of is impact origin, the second, endogenous (Fig. 25).

Among larger forms, the smooth nature of the slopes is visible in Sabine, Ritter, Delambre, Wright and Shaler. In some cases, the relief of the external slopes appears rugged, but their surface on photographs is "blurred" and "sleek," as if, during printing, the photographs had been slightly out of focus. When examined more closely, one can see that the "blurred" appearance occurs because there are no small cracks, walls or craterlets on the surface, which are normally seen everywhere; apparently, they are covered by a thin layer of matter, probably of volcanic origin (Fig. 26).

Hence, on the far side of the Moon at 5°S latitude and 145°E longitude, there is a structure made up of two connected craters with diameters of approximately 25 and 40 km. They stand out due to the characteristic subconcentric fissuring of the lava floor and the same "blurred" appearance of the low, narrow walls. When photographs are enlarged, it can be seen that the wall with the dome-shaped profile overlaps the fissures of the floor and, /74

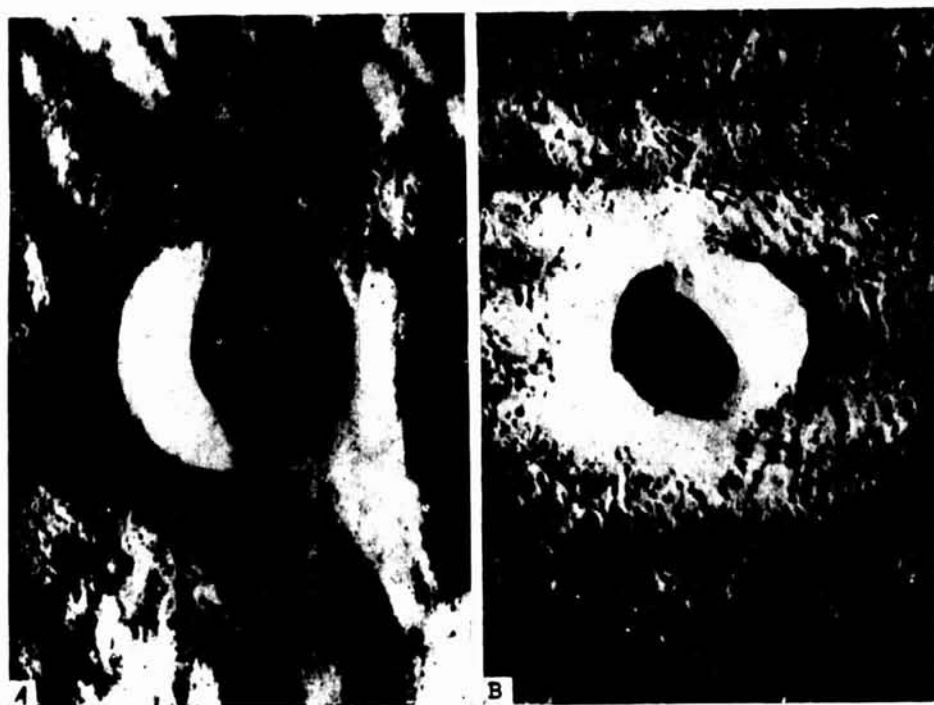


Fig. 25. The external slopes of crater walls.
 A. Copernicus H, diameter 4.6 km, an endogenous crater with smooth slopes and dark aureole.
 B. Mösting C, diameter 3.8 km, an impact crater with dune relief and secondary craterlets.

consequently, the wall is lower than the floor, that is, impact origin can be ruled out.

The smoothed appearance or "blurring" is characteristic of walls of some ghost craters, for example, Gambart and Flamsteed P, for which endogenous origin has been established (Guest, Fielder, 1968).

The indications listed above, if they are sufficiently clearly shown, can be reliable witnesses of the endogenous nature of a crater. Furthermore, there are structures widely represented in lunar craters which could occur in a volcanogenic crater and in a meteorite one affected by volcanism. These are volcanoes, extrusions and lava lakes on crater walls, lava floors, gothic fault systems and terraces.

1. Volcanoes, overlapping the crest of a crater, are seen in volcanogenic craters and in stream-like ray, obviously meteoritic craters, for example, in Tycho, Anaxagorus, Philolaus.



Fig. 26. The crater Kopf. Crater diameter 50 km. The walls are narrow and smoothed out, there are no stream-like ejecta, the floors filled with dark volcanic material, the north crest of the wall is overlapped by a small volcano (a), and the southern one by a mantle of dark deposits (b). A volcanic trench goes down from the crest (c).

In the majority of cases, they are small forms on the crest of a wide, massive wall. But there are large volcanoes overlapping crests of relatively small craters, for example, a crater at 12°N latitude, 76°W longitude, diameter 20 km, with an overall wall length of approximately 6 km overlapped by a volcano with a base diameter of 8 km; another crater, Crüger, has a diameter of approximately 20 km, and there is a volcano of the same diameter on its north wall which overlaps the whole northern part of the wall. Craters with such large volcanoes are presumably volcanogenic, since the magmatic channels in them are mainly on the rim, under the wall of the crater, and not under the center, as follows from the hypothesis of initiated volcanism. Sometimes, an elongated fault is shown in the area by small cracks, furrows and ranges, but a volcano appears when this fault intersects a crater wall -- these craters are presumably volcanogenic (the east part of Struve, Barrow).

175

Extrusions show the volcanogenic nature of the crater only when they are seen over the whole perimeter of this crater (Flamsteed P), or on a considerable section of the crater wall (a crater in the Keeler cirque). In some craters

one can see the overlap of the crater floor by material from its walls (Humboldt), but the quality of the photograph does not allow one to determine whether this is a local overlap or whether it can be traced along the whole internal perimeter; if it is local, it could have been the result of the creep of the crater walls or the effusion of lava on the slope.

Lava lakes on walls are seen in typical endogenous (Alphonsus) and in typical meteorite (Tycho) craters. In Aristarchus, with its steep slopes, there are hardly any horizontal areas where lava could accumulate, whereas there are some lava tongues on the external and internal slopes. In Copernicus, lava tongues fall from some lakes to the crater bottom. (These lakes cannot consist of

debris for the simple reason that they only occupy some relief lows 176 and terrace holes, whereas other lows of the same nature are unfilled.)

2 The flat floors of craters, according to the author, almost always indicate volcanism, although this does not mean the volcanic origin of the crater itself. Relicts of the relief are often seen on flat floors: scraps of crests and the steep toes of small craters which are overlapped by floor material in exactly the same way as mare material overlaps the highland relief. Obviously, this relief appeared on the crater floor during the initial stages of its formation, and was afterwards overlapped by horizontally bedded horizons.

Normally, flat floors have clear contact with the internal slopes of walls, and, if the wall is intersected by faults, these faults disappear at the contact with the floor, obviously overlapping the horizontally bedded material.

If one crater is superimposed on another and the wall of a later crater passes over the floor of an earlier one, the transient forms of this wall can be easily traced: from slightly submerged, with clear internal boundaries (whereas they are gradual over the whole perimeter), to relicts of the wall, which have fallen onto the floor of the neighboring crater and are almost completely submerged.

There are no differences between the structure and position of mare material submerging these craters, such as Archimedes and Plato, and the structure and position of floor material in many highland craters. The only difficulty sometimes encountered is the multiphase nature: dark rocks of typical mare appearance appear in some parts of the light, flat floor -- along the rims of the floor (Humboldt) or occupying almost the whole central part (Tsiolkovsky). In exactly the same way, individual, even parts of light matter on the bottom of craters can overlap light, but more knolly areas of the bottom. There is no difference between old mare rock (Sukhanov, 1969b) filling lows in areas between craters and rock filling crater floors. Moreover, very often they are linked by straits through openings in the crater wall, forming typical crescent crater peculiar to the edges of dark maria.

In some cirques, there is a characteristic crack diagram on the flat floor which, in outline and profile, is similar to mare cracks. These cracks are only seen on the highlands in areas of old maria. It is interesting that sometimes these cracks intersect a central peak or can be traced along the wall of a young crater cut into the flat floor. This indicates that, firstly, the cracks are not a result of simple expansion of lava covers when they cool, but are deeply embedded; secondly, they do not appear immediately, but after a certain time after the flat floors

have formed. A crack diagram sometimes indicates an arc bulging and corresponding expansion of the whole crater floor (Humboldt).

Finally, in some craters there are volcanic vents on the flat floors (Alphonsus), volcanic cones (Copernicus, Aristarchus, Tycho), individual lava flows (Tycho, Tsiolkovsky), and mare ridges (Gassendi); sometimes the floor is filled above the level of the surrounding area (Wargentín).

Only floors where the contacts with the side of the crater are unclear, where the profile is concave or cup-shaped or where there are no submerged relicts, are of nonvolcanic origin. There are relatively few craters such as these among large forms. 77

It is interesting that there are hardly any mare ridges and sinuous rilles in craters; they only appear in thalassoids, which, apparently, are transient forms between craters and maria.

If one allows for initiated volcanism, the central peaks of craters do not show the volcanogenic nature of the crater itself; in this respect, central ridges and dikes mentioned earlier are more hopeful prospects.

3. Until now, little study has been made of gothic structures. This term was suggested by J. E. Spurr (1944-1950); A. B. Khabakov (1949, 1960) calls them "woody knot structures." The first term seems more suitable, since these structures resemble gothic arches inserted within each other. We are speaking of lattice ridge and furrow systems running northwest and northeast, mainly on north and south closures of crater walls (Fig. 27). These lines, straight or slightly curved, go off at a tangent from the wall crest or at a tangent from the internal terraces of the wall (here, they intersect the wall crest, going toward its outer slope); some of the lines continue parallel to each other along the external slopes of the wall. As they move away from the crater, they gradually form the shape of a fan. When they intersect, these lines form a characteristic lattice system with rhombic cells. Normally, they can be traced not only over the solid cover of the crater wall, but into the surrounding area. Incidentally, the cover itself on the northern and southern walls frequently is wider than on the western and eastern ones. Gothic structures are mainly seen in craters with a relatively fresh appearance and deep and wide walls.

When studying these formations, one notices that they are generally confined to the northern and southern fringes of craters. Could this not be linked with lighting which is always from the west or east? In fact, one can sometimes see crossing lines over the whole crater perimeter (Pythagorus, Aristoteles). Later, we shall probably attempt instinctively to show some order where there is none, and draw a crossing network of lines on a random

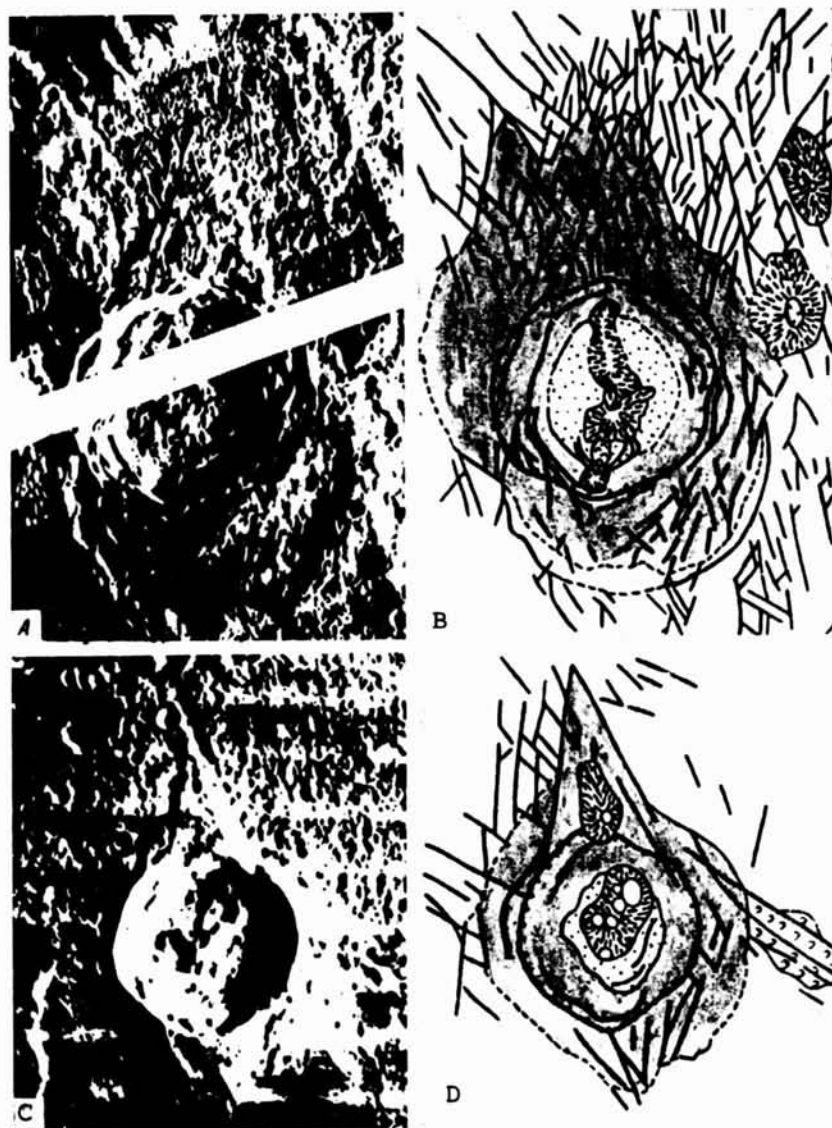


Fig. 27. Gothic fault systems. A, B. The crater Philolaus, diameter 70 km; the faults are marked by fissures, furrows, ridges and craterlet chains. C, D. The crater Markov, diameter 50 km; the southern closure of the wall is partly overlapped by a mare, and the gothic system here has been cut off. The symbols are shown in Fig. 7.

accumulation of knolls and holes. Apparently, this sometimes takes place (Langrenus). Finally, did these forms occur as the result of ejection of material from a crater (and the dynamics of these large explosions is still uncertain) or are they linked with fault tectonics? (The morphology of these structures does not allow them to be considered plicated dislocations as was done by J. E. Spurr).

Careful study of gothic structures shows that, in fact, they all exist, although they are not as extensive as appears at first glance. Terrace-forming faults often pass behind the crest of a wall in the northern and southern areas of the crater. The northern and southern sections of the crest are often cut by furrows, lowered or, vice versa, crowned by volcanoes. Sometimes, gothic structures are more clearly defined on one of the walls, northern or southern, in comparison with the other. Finally, they are not inherent in all young craters, but only in some. Furthermore, indications of volcanism in some craters are linked with gothic systems (Taruntius, Philolaus).

Obviously, gothic systems not only reflect the structure of ejection, but the system of fault dislocations. In other words, it is not known why they are not seen in all craters and why they gravitate towards northern and southern fringes of craters. /78

As has been said in the chapter on the structural links of craters, gothic systems of cross faults are common in two adjoining craters (Werner-Aliacensis, Regiomontanus-Walter, Humboldt, Hecataeus, etc.). In this case, the terraces of one crater are prolonged by faults tangential to them through the wall which is common to both craters and are joined to the terraces of the neighboring crater. Obviously, this indicates the steep fall of terrace-forming and gothic faults -- when there was a smooth fall of terrace faults, they would have been inclined inside each crater, on the opposite side, and could not have been joined by a common fault; consequently, terraces are not the result of a simple creep of crater walls.

Gothic fault systems indicate tectonic stresses (for example, latitudinal compression) when the crater was formed, but they show no indication of the crater being volcanogenic or primary-meteoritic.

4. There is an overwhelming majority of terraces in fresh craters with a diameter in tens of kilometers, among which there are obviously impact forms. Therefore, they cannot be an indication of the volcanogenic nature. But the steep fall of terrace-forming faults shown above and lava lakes on terraces indicate that these faults are embedded deeply, just as other faults on the floors of craters (Fig. 28). Generally speaking, the creep of lunar crater sides, suggested as an explanation for terraces, is problematic: on Earth, steep (up to 40°) scarps 300-400 m high are preserved in effusive rocks; on the Moon this corresponds to scarps up to 2-2.5 km in height, and, moreover, the absence of water should protect them from creep. Therefore, terraces, apparently, should indicate endogenous activity seen in a crater irrespective of its origin.

Only some terraces of its external slopes can indicate the endogenous nature of a wall, but they differ from terraces of the

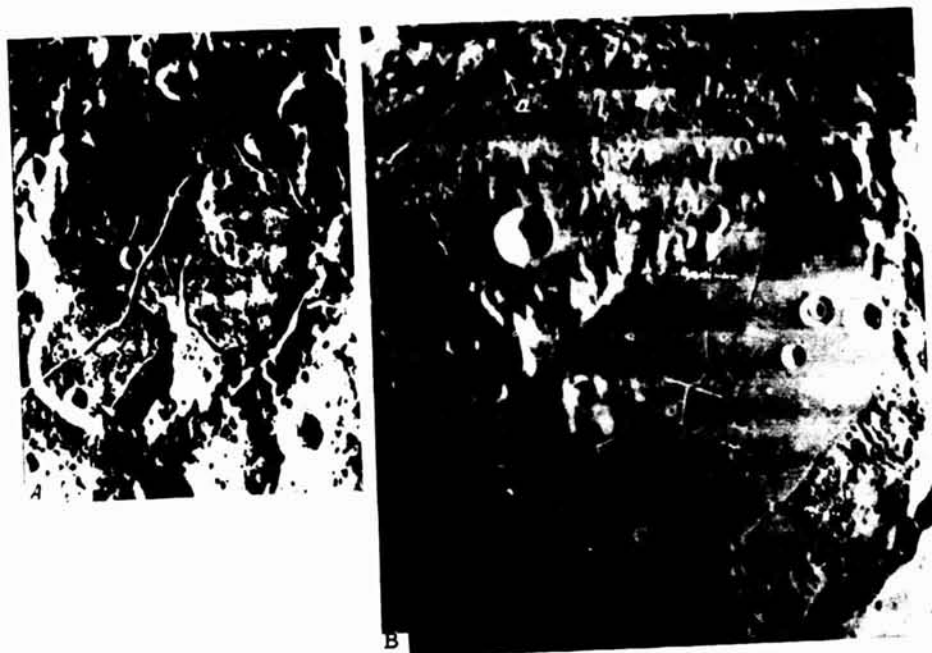


Fig. 28. Cracks on the bottom of craters. A. Repsola (90 km), one of the cracks on the bottom continues southwest and intersects the wall of a smaller crater superimposed on the wall of Repsola; therefore, it did not occur due to the cracking of the lava cover, but is deeply embedded. B. Humboldt. Probably, the occurrence of radiating and concentric cracks is explained by the arch bulging of the whole cirque bottom, as in resurgent calderas. Some of the cracks are overlapped by the latest effusions (a-c). Frame width 120 km.

internal slopes. They are more indistinct and the external and not the internal block has subsided, so that a relatively sharp crest of the wall remains, which is isolated from the gentle external slopes by a distinct bend. This crest either indicates the lifting of layers on the rim of the explosive crater (but during the first subsidences of the internal terraces this crest should sink into the crater) or, which is more probable, the tectonic or volcanic origin of the wall crest. This indication should not be reckoned as being reliable since there is a similar picture during the normal subsidence of a wall into a crater and when cracks and furrows are formed on the external slopes of a wall.

5. The conformity of a crater to any structure when compiling a map was not allowed for, since the majority of these cases can be explained by random coincidence. For example, Lambert is on the

joint of two large mare ridges; but there are so many ridges in this area that it is quite probable that a meteorite fell into the mare ridge. Another such crater is on the southwest wall of Barrow: it lies where the wall intersects the northeast fault zone, but craters of similar size are often seen in the surrounding area; therefore, only the elongation of this crater towards the fault and the appearance of a fault on the crater floor will allow it to be classified as volcanogenic.

There are other features of craters which can be interpreted in /79 two ways; hence, J. E. Spurr described a crater (19°S latitude, 3°W longitude, diameter 80 km) in which, in his opinion, one of the sections is a part of the surrounding area which did not subside into the collapsed crater. However, no other convincing examples of this type have been found, but the depression itself /80 could probably have been formed by several old merged craters with a common submerged bottom.

Unfortunately, only details of craters which are relatively well-preserved can be subjected to definitive genetic interpretation. The interpretation of many old craters is made more difficult by traces of later processes which distorted the appearance of the crater to such an extent that it is often difficult to isolate it among hills, furrows, ridges and craterlets of the old crater outline.

Therefore, at the present time, we have no definite criterion allowing us to tell whether any crater, chosen at will, is volcanic or meteoritic. This is especially true of old, eroded forms. The situation is made more difficult because a great number of large craters, thought to be meteoritic, have undergone volcanic reworking.

However, there are several indications, each of which, being well shown (in the case of detailed photographs and well-preserved craters), makes it possible to determine the volcanogenic nature of a given crater, especially if it is accompanied by other signs. /81 In craters distorted by subsequent processes and when using photographs of insufficient resolution, it is difficult to isolate volcanogenic craters, and this question must be solved in each individual case by a series of indications.

Mare Formations

Apollo 11, Apollo 12, Apollo 15 and Luna 16 brought back lava samples of basalt-like rocks from the surface of the dark (relatively young) maria. Surveyor 5, Surveyor 6 and Luna 17 landed in the dark maria and carried out chemical analysis showing the similarity of the composition of rocks in these areas to the composition of samples brought back to Earth. According to photographs taken in the Orbiter series, it was found that the

morphology of mare areas is close to that of basalt lavas of the pahoehoe type, which agrees with the low viscosity of lunar lava (Weil et al., 1970).

In this way, it can be reckoned that dark mare are formed basically by area effusions of lava of basalt-like composition.

Apart from young, dark maria on the Moon's surface, there are widespread areas of old, light maria. We showed earlier that, according to morphological data, old maria are similar to young, dark maria and only differ from them by their bright color and the rugged nature of the relief, which is mainly explained by the longer meteoritic and tectonic reworking of their surface; this similarity gives a basis to suppose that their composition is similar (Sukhanov, 1969b; Sukhanov, Trifonov, 1969). Without dwelling in more detail on this question, one must however list the signs with which old mare areas can be determined:

1. the leveled nature of individual areas in regions with a rugged highland relief;
2. ingressive contacts ("inlets" and "bays") of rocks of these areas, occurring in basins with formations of the surrounding highland;
3. the overlap of fault systems by rocks of leveled areas;
4. the overlap of highland craters by rocks of leveled areas with the formation of crescent craters and ghost craters;
5. the deficit of craters smaller than a certain diameter within one highland region when there is normal crater density in the surrounding regions (Dodd et al., 1965);
6. filling in of round highland basins (thalassoids) with ring "coastal" ridges (cordilleras) by light rocks with a leveled surface;
7. the gradual transformation between dark, young maria and the light leveled areas. These leveled areas cannot be formed by deep accumulations of dust and debris for the following reasons: a) areas with a rugged relief on the same altitude level and adjoining the leveled areas are not overlapped -- the debris layer must cover all the lows; b) graben-shaped cracks with steep sides and traces of the latest tectonic shifts are encountered on the leveled areas -- they should have been leveled in a debris and dust layer; c) the morphology of these areas is similar to that of dark maria composed of lava.

Many areas of ancient seas, shown on the map, could have other outlines or could not be maria (although it is difficult to understand how else a wide, even surface could have been formed).

However, on the map the scales of mare volcanism are normally understated. This can be seen since the better the quality of photographs for a given region, the greater are the areas of ancient area discernible on them. Most of the regions photographed in sufficient detail are covered by a dense mosaic of ancient mare areas; it is natural to assume that regions not photographed as well have a similar formation.

As a whole, ancient mare formations were formed earlier than the dark maria (Sukhanov, Trifonov, 1969). W. K. Hartmann and J. A. Wood (1971) showed that if the crater density on dark maria, on an average, is accepted as 1, on old highlands it is approximately 32; the values of crater density on old mare areas is distributed in an interval from 2-6 to approximately 28. These calculations do not allow one to determine the absolute ages of individual old mare areas, since neither the reduction rate of the meteorite flux over time nor the amount in which volcanic processes take place in the formation of the crater population are known. However, there is information that the absolute interval between some light and dark maria could be small (Pohn, Offield, 1970). If this is so, it can be assumed that the clarification of some old maria is not linked with their age, but with differences in their substantial composition.

Although mare rocks, undoubtedly, are of volcanic origin and did not appear when round maria were formed, but much later after their formation (Hartmann, Wood, 1971), these basins themselves and the cordilleras are thought by many authors to be the result of asteroid impacts. In fact, an extensive belt of deposits around the youngest ring mare -- Orientale -- gives the impression of a massive one-time ejection (Fig. 29).

It is now difficult to make a well-founded conclusion on the nature of deposits around Mare Orientale and other maria with concentric and radial structures. Therefore, they, like other formations, are shown on the map as being of unknown origin. However, some facts should be noted which speak in favor of the endogenous origin of "ejecta" of ring maria.

1. Radial and concentric fault systems of round maria indicate tectonic activity in these structures. Mare Imbrium, together with Mare Clartitas, Tranquillitatis, Fecunditatis and Australe, lies in a fracture belt which extends over a distance of more than 5000 km almost exactly in an arc of the Great Circle. The belt can be traced from the highland protrusion between Archimedes and Timocharis, through the Haemus Mountains, Julius Caesar, Lamont, Mare Nectaris, Rheita Valley and further to the southeast. In the strip from the Apennines to Colombo, there are right-hand shifts by 10-15 km along these faults. In the Mare Vaporum region, faults in this belt are radial to Mare Imbrium, and are interfingered with other radial faults. If it were not for



Fig. 29. Mare Orientale. The diameter of the external ring cordillera is approximately 1000 km.

their conformity to the planetary deformation belt and their displacement along it, the linearity of this zone could be explained by ejection and not by tectonics.

South of Sinus Medii, many linear tectonic and volcanic structures are visible (the furrow Gylde, the crest Alphonsus, cracks and volcanoes Fra Mauro), which are also radial to Mare Imbrium.

The picture is the same north of Mare Frigoris: a fan of faults, radial to Mare Imbrium, are indeed faults and not ejecta (crests and furrows of the W. Bond-Barrow-Meton region; a furrow along 20°W longitude between Philolaus and Anaxagorus, and others), and along many of them there are movements, distortions of craters walls and volcanic manifestations. With this

number of radial faults, which differed in good photographs, there is strictly no room for "ejecta." D. J. Milton was forced to assume that the knolly area of craters Delambre-Abulfeda, after the formation of Mare Imbrium, were overlapped by cover of volcanic material which concealed traces of a radial stream-like nature linked with hypothetical ejecta from Mare Imbrium (Milton, 1968). In fact, there is no stream-like nature here, and most likely there never was, but only subparallel faults which can be seen well in knolly areas.

2. The differences in the structural diagram in individual "ejecta" sectors of Mare Orientale allows us to assume the endogenous nature of these "ejecta." In the northwest and southeast, radial and linear forms are mainly developed in the "ejecta" field which stretches further here than in the northeast, where the subconcentric structures on the surface diagram become noticeably curved and looped. It is possible that a fault zone, similar to that connecting Mare Imbrium and Mare Fecunditatis passes through Mare Orientale in a northwestern direction. Faults -- cracks and

faults tangential to the central basin -- can be discerned in the "ejecta" field. It is highly probable that a considerable amount of radial "ejecta" are also faults and strips of volcanogenic manifestations.

According to V. G. Trifonov, fault systems which surround maria developed in several stages, and this does not agree with the meteoritic hypothesis; there are also signs of the prolonged growth of "coastal" cordilleras.

3. Analysis of the degree of eroded nature of craters showed that deposits around some maria are younger than the maria themselves (Nectaris, Humorum). These deposits should be considered as volcanogenic (Pohn, Offield, 1970).

4. Some cordilleras consist of volcanoes (at least partially): the internal cordillera of Mare Orientale, the Alps². Consequently, concentric faults around maria are deep-lying and in their time were magma-carrying channels. This is borne out by the concentric depressions with old mare rocks in the back sections of cordilleras. The centers of concentric cordilleras are normally somewhat shifted relative to each other, and this gives reason to suppose that the internal concentric cordilleras are volcanogenic.

5. Positive gravitational anomalies below round maria (mascons) also indicate the endogenous nature of mare basins. Four hypotheses were suggested to explain the origin of mascons.

A. P. M. Muller and W. L. Sjogren (1968) believe that the anomalies were caused by gigantic (several tens of kilometers in diameter) metallic asteroids which buried themselves below the maria. But, first, such an asteroid would not remain in the place where it was buried, but with its own weight would force its way toward the center of the Moon (O'Keefe, 1968). Second, it would scarcely be able to bury itself below the mare: the explosion during impact, apparently, would be near the surface (Shteynberg, 1969) and asteroid matter would be scattered over great distances. Thirdly, all large maria with mascons are on the near side; maria on the far side are relatively small and

² This explains why the axis of the Alpine cordillera is at an angle of 60° to the axis of the Apennines-Caucasus cordillera and is not a prolongation of it. Apparently, the Apennines and the Alps occurred in different ways: the first from tectonic movements, the second mainly as the result of volcanism. Therefore, the radial Imbrium system of the northern polar region does not begin at the Alps, but at the northern edge of Mare Frigoris, where the geometric rim of the basin of Mare Imbrium passes and where the "true" cordillera should be.

could scarcely be linked with large mascons, since there is a direct connection between the diameter of a mare and the size of a mascon. At the same time, it was shown that when one mascon is formed, the Moon should quickly be turned with that side where the anomaly occurred towards Earth, and therefore the formation of all mascons on one side ought to be geologically simultaneous (Reinhardt, 1969), which is difficult to explain assuming an asteroid bombardment.

B. According to the second hypothesis, the anomalies are caused by the filling in of mare basins by heavy basalt, the highlands being formed of a light matter (Conel, Holstrom, 1968). Where the difference in density between mare and highland rocks is 1 g/cm^3 , the mare should be filled with basalt to a depth of 15 km; if one accepts a value of this difference which agrees better with the latest information and is $0.3\text{--}0.5 \text{ g/cm}^3$, the depth of basalt is 30-40 km. In this case, it is incomprehensible why there are mascons in some maria and in others there are none, and, even if negative anomalies occur, only the matter of maria, according to all information, has a close density, and the depth hardly varies at all. Judging from the inclination of the "shores" of submerged craters, the depth of Mare Nectaris and Mare Humorum is only the first kilometers, and there are mascons in them. /85

C. The third hypothesis suggests the stratification of lunar matter into a light crust and a denser mantle (Kropotkin, 1971; Markov, Sukhanov, 1970; Wise, 1970). Anomalies occur above the protrusions of mantle matter and reflect the relief of the lunar mantle; the depth of the crust is 50-200 km. This hypothesis would explain the existence of magmatic foci in a solid Moon -- fusion occurred at the base on the crust, whereas the rocks of the mantle, lying at a lower depth, were too infusible to yield melts, and could only be softened and pinched in the weakened zone, forming protrusions -- mascons.

D. The fourth hypothesis is a combined one (Wood et al., 1970). It assumes the simultaneous existence of a mantle protrusion and the filling in of the maria by compact rocks, since the mantle sometimes emerges onto the surface. It is believed that highlands are composed of anorthosites and the mantle and the maria rock of basalt. However, the distribution of anorthosite on highlands is still unclear; the question will remain open until the composition of highland rock is analyzed.

Thus, the dark maria of the Moon are basically formed of basalt-like lava and sills. The light (old) mare areas (according to all information) are also formed mainly of lava. Their composition is unknown, but, apparently, is sufficiently uniform by area and is probably close to the composition of the lava of dark maria. The structure of mare cordilleras and belts around

concentric maria is caused, to a considerable extent, by tectonics and volcanism; however, it cannot be denied that there is a possibility here of extensive mantles of ejecta from some maria.

Types of Volcanogenic Craters of the Moon

Thus, supported by a number of signs (the structure, position, interrelation with neighboring structures), we can reckon that many craters are volcanogenic formations. The structure of these craters is quite diverse; the number of indications showing their volcanic nature varies from crater to crater. But nevertheless, some groups of craters have similar characteristics and differ from other groups of craters (also believed to be volcanogenic). Therefore, in the first approximation, some types of craters can be shown, and the most characteristic examples of each type can be given.

The boundaries between types is quite indistinct. In some craters, there are combinations of structures, characteristic of two or three different types. Moreover, there are many craters occurring mainly through impact and later complicated by volcanism. It is difficult to classify old, badly eroded craters to a certain type, but normally they are of a volcanic nature.

Nevertheless, this approach looks more promising than the random description of nonsystematized craters and makes it possible to isolate the most typical volcanogenic forms.

Concentric Craters

/86

This includes formations with a diameter from 20 to 100 km along the crest of the external wall; the most typical have dimensions between 50 and 80 km. In craters of this type, apart from the normal wall, there are additional concentric structures normally on the flat (submerged) floor of the crater. These structures are easily discernible by the very extended subsidence terraces of their internal walls.

A concentric structure can be in the form of a continuous or broken wall; it can consist of a wall and fissures; there are open walls in the form of a crescent and complex systems of concentric ranges, furrows and fissures. Sometimes, concentric structures are found not along the center of a crater, but displaced towards one of the sides. Sometimes, the external and internal crater walls are closely linked and pass directly one into the other. In Pitatus, the northern part of the crater wall is a single formation, and the eastern and southwestern parts are divided into two concentric walls by crater furrows. Such cases indicate the endogenous origin of the internal and external walls: the asymmetrical

arrangement of the internal wall does not agree with the impact hypothesis, and its close link with the external wall shows that they have an identical origin. There are strips of lava, younger than the lava of the central part of the floor between the external and internal concentric walls, which indicates activity of a ring strip along the crater wall.

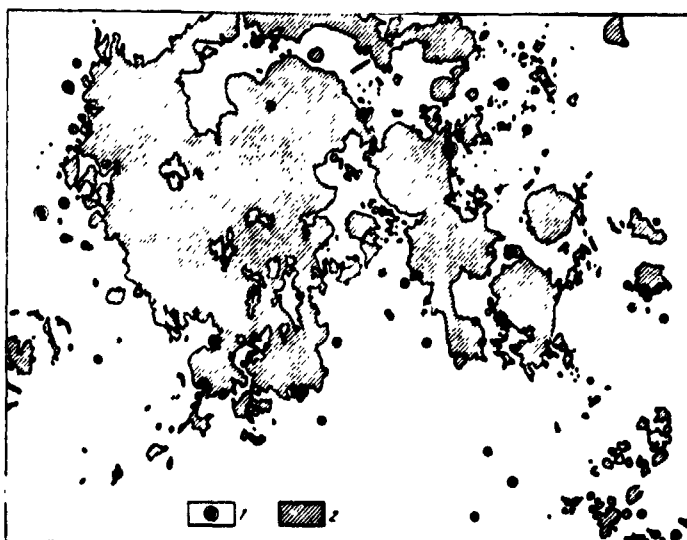


Fig. 30. The distribution of concentric craters on the near side of the Moon ($\pm 100^\circ$ along the longitude): 1. craters of various sizes; 2. dark maria. Most of the concentric craters are on the edges of maria.

The fact that concentric craters exist (there are approximately 40 of them) among the large number of craters of the "normal" appearance shows the special nature of their formation. It is even more notable that most of the craters of this type lie on the edges of maria (Fig. 30), and well into the highlands they are also normally linked with areas where old maria were widely developed. A conclusion can be suggested that the appearance of a concentric structure inside craters is genetically linked with the formation of maria. For example, it can be suggested that when impact craters are submerged, internal concentric structures form. In this case, the ques-

tion of the nature of the external walls would remain open. However, in the majority of craters near maria, there are no concentric structures, irrespective of the degree of submersion and age. Obviously, this selective concentricity, which is only manifested in some craters near maria, indicates the specific nature of the internal formation and the nonrandom, that is, endogenous origin of these craters.

Since concentric structures have a small vertical range, it is possible that in some extensively submerged craters they are buried beneath the mare cover.

Below, the most characteristic concentric craters are described. Each one of them can be approximately reckoned to be representative of one of the varieties of concentric structures (although there are transient forms among them).

1. The first variety are craters of the Posidonius type with clearly defined concentric ridges and fissures, separated from the wall by a strip of mare rock (Fig. 31, see also Fig. 22).



Fig. 31. The Gassendi cirque. The internal knolly part of the floor with concentric fissures (a) separated from the wall (b) by a strip of mare rock (c), on which can be traced the prolongations of mare ridges approach the wall from the outside (d): probably, this strip is separated from the mare by a strip of extrusive new formations making up the crater wall. Frame width 80 km.

Posidonius. Diameter 85 km. It is situated on the boundary of Mare Claritas and Lacus Somniorum and is extremely submerged. The concentric structure is represented by a ridge (a single one or divided into several subparallel ranges) and fissures: in the east by a simple cleft with a somewhat elevated western side, in the west by a sinuous furrow, a direct prolongation of the concentric ridge. This furrow, which extends to the northwest, joins the crater wall and forms a boundary between the wall and the flat floor. The whole structure is shifted to the southeast from the center of Posidonius and in the southeast directly joins its wall. There is, as it were, a third concentric structure in the center -- a crescent of separate knolls and a post-mare, 10-km crater -- a craterlet with a central peak and a small eccentric ejecta field.

187

In the southern part of the crater, where the internal and external walls join, there are several dome-shaped elevations with craterlets on the summits and signs of overlap of neighboring

linear structures; obviously, these are separate volcanoes. The crest of the external wall in the east and southwest is separated from the external part of the wall by a clear-cut scarp (the crest is higher and steeper than the external part) or chains of craterlets. Apparently, the whole crest is composed of volcanic products piled up along the ring fissure (a similar crest is visible near Taruntius). In the northern parts of the wall, the structure of its external slope is similar to that of the adjoining highland and, probably, the wall here is formed by elevated highland rocks.

The external zone of the wall in the east is a concentric-range structure; in the south this zone is isolated from the wall of Posidonius, and it falls in the form of a tongue to the floor of Chacornac; it is difficult to consider it as a result of meteoritic ejection.

It is generally characteristic that Posidonius does not have a stream-like nature but only concentric smoothed or sharp walls. But there are traces of a ray system less than 100 km from the crest of the wall.

The crater's volcanic origin is not only confirmed by its structure, but by its interrelations with adjoining Chacornac, one of whose walls is covered by the wall of Posidonius and the other merges with it (with impact origin, both walls should be overlapped). Close to Posidonius is the elongated, concentric Dariell (20 x 30 km) and another concentric crater with a characteristic "petal-like" form (13-14 km). /88

These features cannot be explained by the meteoritic hypothesis: eccentric ranges, fissures and rilles touching the wall, the interrelationship with Chacornac, the nearness of two concentric craters, and the absence of radial "ejecta." Therefore, Posidonius should be considered as one of the typical craters of endogenous origin.

Inghirami. Diameter 100 km. Situated 1000 km from the center of Mare Orientale, it is included in the development region of radial and concentric structures around this mare.

The radial linearity is particularly intensively expressed in the sector from Mare Orientale to Inghirami; the same strip also extends to the northwest from Mare Orientale, whereas in the northeast and southwest from Mare Orientale the radial linearity is expressed to a lesser degree. In this way, the crater falls into the ridged and furrowed relief strip which passes through Mare Orientale in a northwestern direction. It is extremely probable that this relief, to a considerable extent, was formed by masses of incoherent material which fell here after an explosion and formed the primary basin of Mare Orientale; however, without doubt,

62

there are major faults here in a northwestern direction. In particular, the Inghirami Valley, extending from Mare Orientale to the crater Inghirami, is a rectilinear graben approximately 150 km in length and 30 km in width.

The crater is at an intersection of a strip of northwest linearity with a gently sloping structural scarp which can be traced in a northeastern direction perpendicular to the linearity; the scarp is marked by a craterlet chain, and to the southeast of it, the terrain is overlapped by old mare covers. /89

The crest of the crater wall is polygonal: it consists of aligned segments, oriented at a northwestern and northeastern bearing. Thus, one of the segments is a prolongation of the structural scarp mentioned and the other a direct prolongation of the side of the Inghirami Valley.

The external boundary of the wall can only be well traced in the east, where it adjoins the even surface of a mare type. Here, the wall has a soft and smooth appearance; the linearity almost disappears. In the remaining areas, the wall is covered by furrows, grooves and knolls as is the adjoining area, and its boundary is arbitrarily marked. Inghirami does not have a natural radial or looped ejecta pattern, although the crater looks quite fresh with a clear-cut crest and a deep floor. The internal slopes are terraced; the back part of the terraces are depressed and similar to chains of merged craterlets. The crater floor in the central part is covered by subconcentric furrows and ranges; furthermore, a curved chain of smoothed "sleek" knolls is visible on the bottom. This system of furrows, ridges and knolls forms a roughly shaped crescent, open to the east. A strip of mare material with an even surface and clear-cut boundaries extends from the external side of the crescent under the south and east sides of the crater.

The northwestern linearity intersects the wall of Inghirami, goes down to the its floor, deviates to the east, and here some furrows dissect the smooth knolls at the bottom, and others join at a tangent with the subconcentric system of furrows and ridges.

Determining the age of the crater depends on the genetic interpretation of adjoining structures. As a whole, mare rocks of Altaic age overlap the linear structures of the area, and the linearity, in its turn, cuts a crater wall. In such a case, mare rocks should overlap the wall of Inghirami, as is seen with Posidonius. But no clear-cut contacts and overlaps are visible; therefore, one can assume the prolonged development either of the northwestern linearity or the wall of Inghirami.

Features of the crater structure indicate its volcanic origin: the link between segments of the polygonal wall and tectonic lines

of the terrain, the absence of traces of a central ejection on the walls, holes in the back of terraces, a crescent of smoothed knolls and concentric structures on the bottom, strips of mare material along the internal side and two triangular basins on the bottom (small calderas).

It is interesting that approximately 100 km northeast of the center of Inghirami is a 13-km crater with concentric structures on the floor and a 30-km crater with a sharp wall crest, but with smooth internal slopes and a deep flat floor -- both, apparently, are volcanogenic.

2. The second variety of concentric craters differ from craters of the Posidonius type in that the concentric structures in them are represented by a belt of small ranges and fissures, directly adjoining the internal side of the crater; the central part of the floor is smoothed and depressed (Fig. 32).

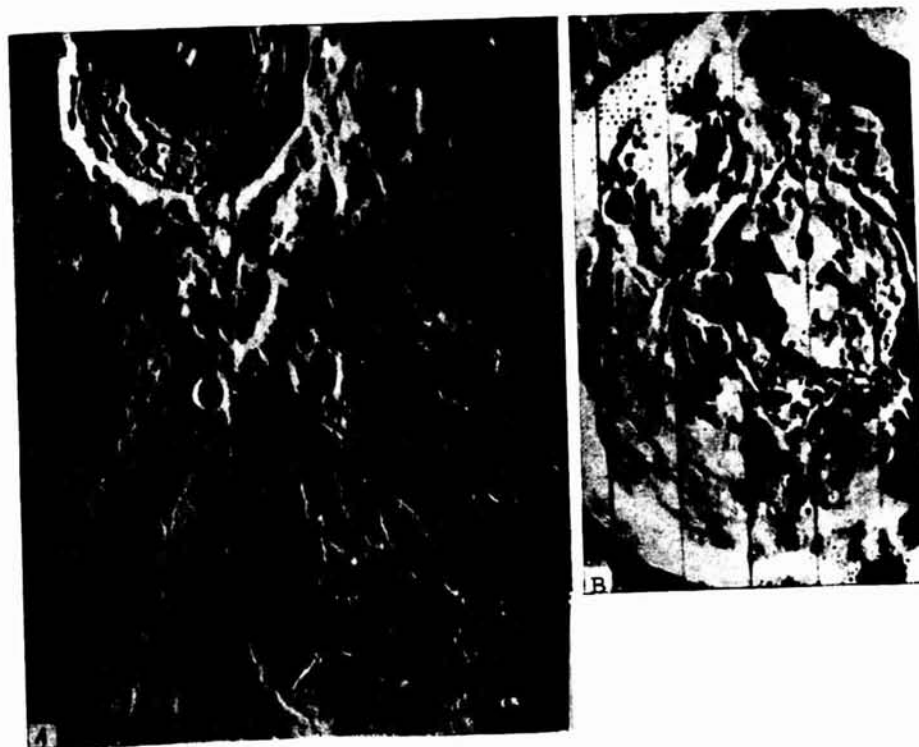


Fig. 32. Concentric craters: A. Taruntius, diameter 60 km. The central part of the floor is submerged and bordered by a belt of concentric ranges and furrows. Among linear structures and chains on the adjoining terrain there are directions, radial and tangential to Taruntius. B. Vitello, diameter 37 km. The central part of the floor is somewhat depressed and leveled.

Vitello. Diameter 45 km. It is characterized by a smoothed wall without any flow formation whatsoever. The wall has a sharp crest, and is, as it were, cut off from inside by fault planes. /90
The concentric zone on the floor, adjoining the wall, is as smooth as the external slopes of the wall; one has the impression that it is sprinkled with incoherent material. Probably this zone (7-10 km wide) is depressed sections of the initial wall reworked by volcanism (lava tongues extend from several craterlets, other craterlets are more dense, although they are on the old sections of the floor, that is, they are not meteoritic).

The central part of the floor is relatively even and separated from the concentric belt by a ring of furrows (including sinuous rilles which enter the ring which, therefore, are of fissure and volcanic, and not erosive, origin). The central peak is 10 km in diameter and consists of 5-6 merged volcanoes.

According to the nature of the wall and the internal concentric belt, it must be concluded that Vitello is a volcanogenic crater which was widened when internal sections of the wall were depressed along the ring faults.

Taruntius. Diameter 55 km. The crater is notable in that one can see, to a certain extent, volcanic-tectonic and secondary impact elements in the ejecta field surrounding it.

The crater is at the intersection of the northeast neck between Mare Tranquillitatis and Mare Fecunditatis with northwest fractures, expressed by the Cauchy Fault and fissures of the mare ridge. Here, the walls deviate from the northwest as they approach Taruntius (at a distance of 5-8 radii from it); they become submeridional and merge with the range relief near the crater. The same system, although weaker, is visible on the crater's north edge. In this way, the crater is characterized by the "gothic" system of crossed faults caused by the tectonics of the region. /91

The crater wall is divided into the external ("ejecta field") and the internal (a narrow ridge, divided from the external field by a clear-cut bend). The crest is 5-10 km in width; the internal and external slopes have an identical inclination. This isolation of the slope allows one to believe that it occurred independently from the "ejecta field" and, consequently, is of endogenous origin.

The internal part of the crater is 2/3 filled by concentric ridges, furrows and fissures. The crater diameter has been enlarged more than twofold due to the gravitational creep and could hardly have preserved a high ring ridge; therefore, the concentric structures, obviously, occurred due to endogenous forces.

The central field of Taruntius is composed of a dark matter and is clearly defined. The central peak (surrounded by several small cones) looks like a volcano with a 7-km crater, open to the south; a 6-km chain of merged craterlets leaves it to the south.

In this way, Taruntius can be considered a sufficiently reliable example of a volcanic, tectonic structure. In this respect, its "ejecta field" is of special interest. On telescopic photographs it differs from the fields of other postmare craters by its somewhat crater "submersion." During closer examination, the following can be seen. Furrows and ranges around the ring ridge are not oriented radially to the crater, but mainly at a tangent to it. Obviously, some ranges in the southeast sector are not ejecta, but walls and peaks of small (10-15 km) craters. (Incidentally, near the crater directly south of the wall of Taruntius, the side facing Taruntius is not only overlapped by material from the latter, but is depressed, that is, the wall, as a whole, has somewhat subsided.) Several ranges of "ejecta" change unnoticeably into typical mareridges. Many craterlet chains and furrows are also linked with these ridges, and therefore cannot be secondary impact ones. Some long chains extend in almost parallel lines to the northwest and, to a lesser extent, to the northeast, at a tangent to Taruntius; they change into faults and ridges; they are doubtless of endogenous nature.

A random swarm of craterlets and short chains radial to Taruntius could be of impact origin. However, the light rays are only linked with some groups of craterlets, and many of the same dispersed craterlets lie outside of rays, and the mechanism of their origin could be different. Many short craterlet chains and some rays, for example, the ray from Taruntius to Taruntius G, gravitate not so much to the center of the main crater as to the remains of craters on the external slopes of the wall; therefore, it is possible that ejecta are not linked with the main crater, but with the peripheral ones. The length of well-marked rays is approximately 100 km (as in Posidonius); debris from this peripheral crater will cover this distance with an initial speed of up to 300-500 m/sec, which does not exceed the ejection speeds of large volcanic explosions.

The example of Taruntius not only confirms the volcanic origin of concentric craters, but poses the question of the origin of the ridged relief surrounding many large young craters. Possibly, this relief occurs (at least partially) as the result of movements and volcanism along faults around the craters. /92

3. The third variety are structures of the Sabine and Ritter type. The concentricity is poorly expressed and is manifest in the form of arc scarps and fissures; the central platform may be raised relative to the marginal areas of the floor (Fig. 33).

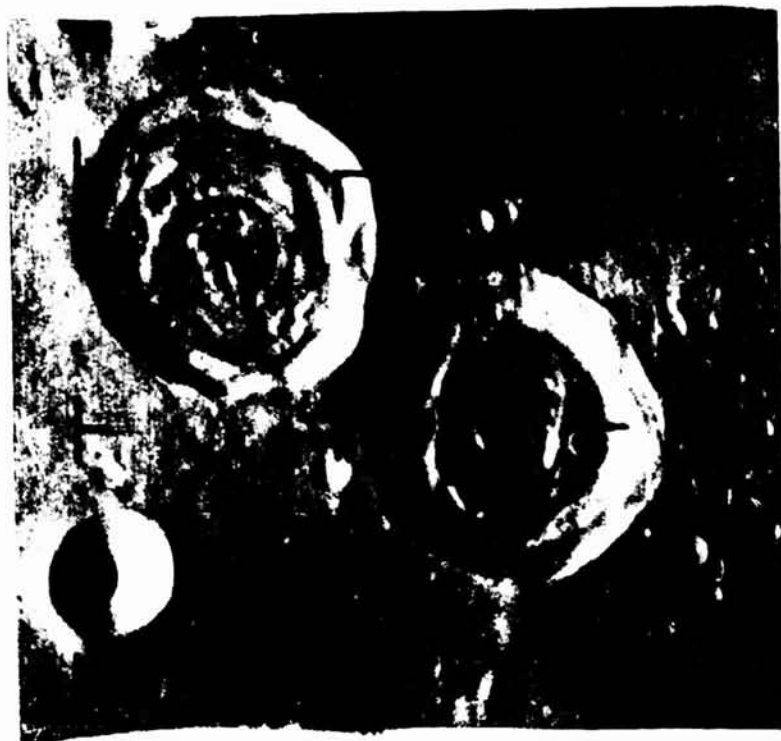


Fig. 33. The craters Ritter and Sabine. Both craters (the diameter of each is 35 km) are characterized by smooth external slopes and concentric structures on the bottom.

Sabine and Ritter. These craters were interpreted by American researchers as volcanogenic structures -- calderas -- according to photographs taken by the Ranger 8 automatic station (Wilshire, 1966; De Hon, 1971). This conclusion was based on the study of structural details of the walls of Sabine and Ritter: the walls of both craters overlap the mare surface; however, no radial pattern nor secondary impact craterlets around the craters were seen. Incidentally, the same conclusion using the same photographs was reached for Delambre (Milton, 1968). It was also noted that the half-ring ridge on the floor of Sabine flows across its southern wall and continues to the mare (Sukhanov, 1969a; Guest, Fielder, 1968). This indicates that the ridge and concentric structure are deep-lying and are formed by volcanic and tectonic processes. /93

In fact, the external slopes of Sabine and Ritter have a very soft relief and their boundaries are blurred, although both craters are postmare ones, since they overlap the graben-shaped fissures on the mare surface. Postmare craters of this size (approximately 35 km) are believed to be impact ones, surrounded by radial or looped "ejecta." The wall creases of both craters are steeper and, in plan, have a characteristic "petal-like" shape.

Obviously, part of the primary walls is submerged inside the craters along faults.

Probably, remains of these ring faults are also manifest in the form of semiarcs on crater floors. Here, the central round blocks of the floors remained submerged and formed slightly raised platforms (a central raised platform such as this is clearly visible in the 80-km Gambart J).

The western edge of the platform of Sabine is raised and forms a braid-shaped wall which continues south at a tangent to the central platform, intersects the crest of the crater wall and its external slope, and ends on the boundary with the mare surface as a volcano-shaped knoll. Sabine and Ritter lie at a point where the highland intersects the system of mare ridges extending from the northeast. The direction of the braid-shaped ridge in the south coincides with the direction of these ridges.

There is no doubt about the endogenous nature of these twin craters. In this respect, attention is drawn to the characteristic shape of the wall crests in plan, which differs from the circular one with gently sloping semiarc scarps characteristic of petal-like craters.

As opposed to flow-like craters, where the terraces are normally distributed uniformly over the internal slopes of the wall, in Sabine, Ritter and other petal-like craters, the main steep fault runs down from the wall crest and there are weak traces of terracing at lower levels.

Obviously, the evolution of craters of the Sabine type is accompanied by the widening of the crater and the submersion of the internal parts of the wall; otherwise, it is difficult to explain how the present-day profile of the crater wall appears.

Among craters of this variety, there are frequently forms where the concentricity is only manifested by fissures on the floor. A pair of twin craters at 5°S latitude, 144°E longitude is characteristic of this. The diameter of one is 40 km, of the other, 25 km; the craters adjoin, and the closure between them almost disappears. The floor of the craters is flat and covered by concentric and broken furrows from 0.2 to 1.5 km in width; in places, the furrows are overlapped by tongues of the latest material with a softer, "blurred" surface structure; obviously, this is lava and pyroclastics. The width of the walls varies from 6-8 to 20 km; they are lighter than the bottom of the craters; the number of small (hundreds of meters in diameter) craters on the gently sloping walls varies from place to place by 5-10 times, and, in some areas, they are almost indiscernible, that is, the wall is of different age. The structure of the wall is formed by random knolls and basins without any trace whatsoever of flow structure.

The main thing is that in some areas the wall is superimposed on floor, fissures, here there are many craterlets on the floor, but hardly any on the wall. As a whole, the walls of this pair of craters are similar to the extrusive walls of Flamsteed P; there is even a characteristic talus ridge at the foot of the eastern wall of the smaller crater.

4. The last type of concentric craters are represented by simple ring ridges, which, in places, are divided into parallel branches along the ridge crest by furrows and crateret chains (Fig. 34).

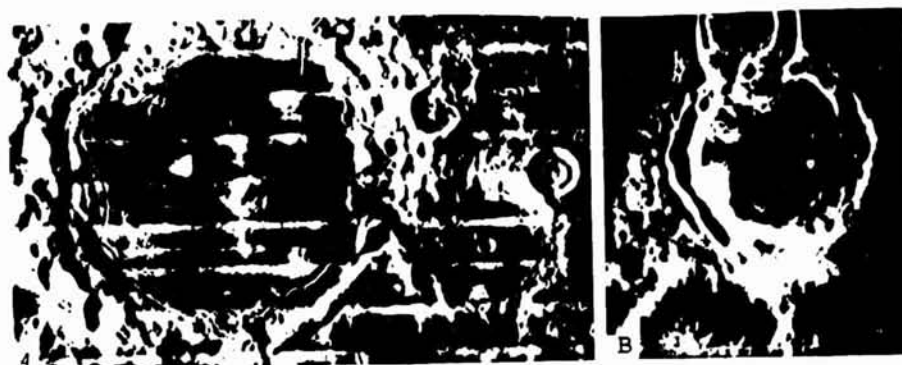


Fig. 34. Concentric craters. A. Pitatus, diameter 100 km; a. the double crater Marth; B. A structure from two twin craters with diameters of 40 and 20 km at 35°N latitude, 77°W longitude.

Pitatus. This is the largest representative of the variety described (100 km). The internal terraces in it are hardly expressed, whereas a chain of merged craterlets pass along its wall crest -- as it were, nuclei of ring grabens, which in other concentric craters separate the internal wall from the external one. A concentric furrow extends along the edge of the floor. The wall consists of soft merged knolls and, when comparing Pitatus with other volcanic craters of similar appearance, it can be assumed that this is a light, smoothed, relatively young wall and is of volcanic origin, as is Flamsteed P. /94

Of the smaller craters, two merged concentric rings at 35°N latitude, 77°W longitude should be noted (20 and 40 km). The transition of the external wall of one crater into the internal wall of another, their brightness, their smoothed surface -- all this, undoubtedly, indicates the extrusive origin of both walls. The ring valleys, dividing the concentric walls of this structure,

in places are replaced by furrows from merged craterlets on the crest of a single wall. This unites craters of the Pitatus and Posidonius types.

In this way, by examining concentric craters, the conclusion can be reached that they are all formed by volcanism, where the subsidence of calderas is combined with the formation of ring extrusive and extrusive-pyroclastic complexes.

Primitive Rings

Formations of this type cannot always even be called craters; they are low ring ridges, sometimes open, without floor subsidence. The nature of the ridge surface, normally smoothed and light, and, according to some signs, younger than the surface of maria (as a rule, these forms are only discernible on maria) distinguishes them from ghost craters (submerged relicts of normal craters). There are three varieties of primitive rings: the Lamont, Flamsteed P and Gambart types (Fig. 35).

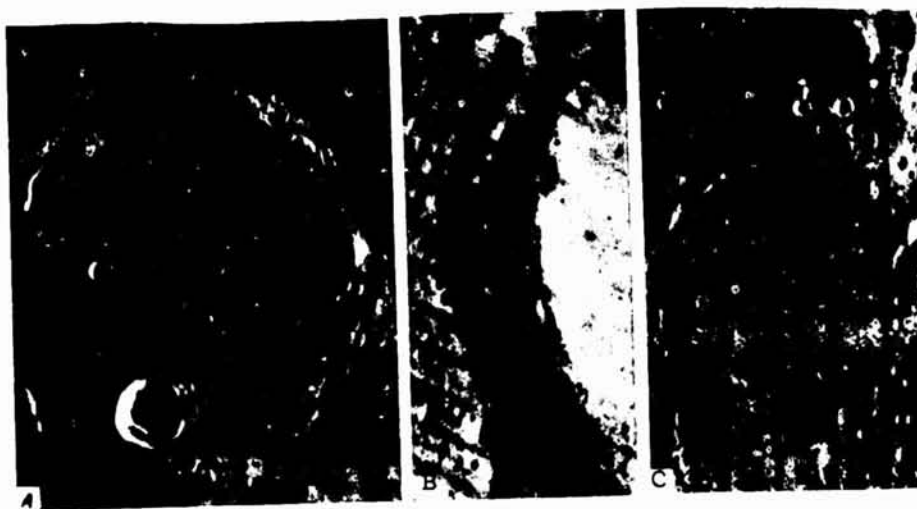


Fig. 35. Primitive craters. A. Flamsteed P, an extrusive ring with a diameter of 120 km. B. One of the knolls making up the Flamsteed P ring. C. A ring structure, formed by mare ridges(a) and a ring scarp (b), bounding the highland in the Littrow fissure region (the bubbles are image interference).

Lamont. A roughly outlined oval structure, formed by mare ridges, with a dimension of approximately 100 x 150 km over the external oval. It is situated on the intersection of the northeast

/95

mare ridge system, tracing a sharp bend on the surface, with a prolongation of the belt of northwest-trending faults from the Apennines (these faults are also traced by mare ridges). In the southwest, the mare ridges are set against the concentric crater Sabine; in the northeast they are interlaced with the complex horseshoe shaped structures near Jansen). Many mare ridges are subradial to Lamont, some merge with its marginal ridges and other intersect them. On large-scale photographs one can see fissures and graben-shaped furrows, concentric to the walls of Lamont.

Undoubtedly, the whole structure has an endogenous origin. Here, the floor of the mare has been submerged quite deeply, since there are no antemare relief steps in the direct vicinity of Lamont. Obviously, they should be considered as dikes and sills which have occurred along extended fissures. The Lamont example indicates the possibility of the formation of ring magma-conducting fissures without a noticeable shifting of the central block.

There are several craters of this type in Mare Fecunditatis, Nectaris and Nubium. These are either new formations, or the mare ridges trace old submerged craters.

It is characteristic that the crater Flamsteed P is also on the southern edge of Oceanus Procellarum, where there are many interlaced, curved mare ridges.

Flamsteed P, a crater with a diameter of 120 km, is a broken ring of lava domes, linked with a system of ring mare ridges (O'Keefe et al., 1967; Guest, Fielder, 1968). The rocks of the domes are superimposed onto mare craters, and their surface is younger than the surface of the mare, since it contains fewer small craterlets per 1 unit of area. Near the base of these domes can be seen small ridges, apparently formed from blocks which have crumbled from them. Since no such small ridges are visible around the majority of lunar volcanoes, one must assume that they are linked with the formation method of domes, which is: the domes must not be lava, but extrusions and small ridges at the foot of them, that is, extrusive talus slides. The profile of the domes also agrees with this: on one side there is a gradual transition to the mare surface and on the other, a steep scarp along the fault. Apparently, the extrusive body moved out irregularly.

/96

Flamsteed P is possibly a new formation, but it is just as possible that these domes trace the crest of a submerged cirque, the ring fissures of which continued to produce magma after the cirque was overlapped by the mare.

J. E. Guest and G. Fielder believe that most of the ghost craters in the mare and on the highlands are of a similar nature. Apparently, nevertheless, the ghost craters are of two types: the remnants of walls of submerged cirques -- irrespective of their

origin and new formation -- extrusive rings. These half-rings of extrusions (without subsidence of the caldera) are also seen on Earth (Ehrlich, Trukin, 1969).

In some primitive craters (Opelt), part of the ring is formed by mare ridges (as in Lamont), and part by clarified crests (as in Flamsteed P). This indicates the similarity of origin of rings of both varieties. However, it is not clear whether the extrusive rings are a more mature form in comparison with Lamont, or if they do not pass the Lamont stage. On one hand, examples are known when young volcanoes or extrusions are set out on mare ridges. Further development of this process would have transformed a crater of the Lamont type into one of the Flamsteed P type. But, on the other hand, mare ridges sometimes trace the crests of old submerged cirques (a system of ridges west of the Straight Wall, the north closure of Letronne). In this case, Lamont is the final stage of development of the cirque. Primitive craters have much in common with the internal rings of concentric craters.

Gambart. Diameter 30 km, it has a narrow even wall and a flat, high floor. There are no secondary craters, radial structures or terraces on the wall. The only complication on the wall is a small knoll with a summit craterlet right on the wall crest. This knoll is interpreted as a separate volcano and the whole ridge, apparently, is made up of effusive-pyroclastic accumulations along the ring fissure.

Another example of this type is the crater Kopf (Mare Orientale) with a diameter of approximately 50 km. Here also there is no flow formation and secondary craters; the floor is composed of dark mare rocks (although the crater lies on a relatively old substratum). As with Gambart, two volcanoes are visible on the wall crest, dark flows from one of which run down from the internal and external slopes of the wall. McCauley (1968) compares this ring with the neighboring stream crater of the same size of a similar age and makes the conclusion that the first crater is endogenous and the second is of meteoritic origin.

Apparently, the rectangle of Boscovich P, the long narrow ridges of which are extended according to the general fault strike of the adjoining area, are primitive craters.

There are few primitive craters in a pure form, but varieties are often seen which are transitions to craters of other types, (Wolf, Davy, Palmieri, Prosper, Crüger). It can be assumed that craters of the Gambart type represent the initial stage of craters with subsidence, terraces and deeper walls. Volcanic craters such as these are classified as mature craters.

/97

Mature Craters

Wright and Shaler. Both these craters have approximately the same diameter (50 km), they are very similar in structure and form a pair with adjoining rims, the axis of which is directed towards the center of Mare Orientale and subparallel to the tectonic valleys of Inghirami and Baade (Figs. 36 and 37).

Such an arrangement of identically constructed craters of similar dimension allows them to be considered as endogenous -- in fact there are no craters of approximately the same size in the vicinity, and only five craters in Mare Orientale have a similar structure. Of these, four are also accurately placed in pairs: Krasnov and the nameless crater north of it and Petit and Nicholson. In the second pair, the craters have a diameter of approximately 50 km, and, in the third, 40 km. If these postmare craters were impact ones, they would be accompanied by a family of similar craters, chaotically strewn in the area of Mare Orientale, and the direction of the crater pairs would not be linked with the tectonics of Mare Orientale.

The Krasnov pair is poorly preserved, but Wright-Shaler and Petit-Nicholson, undoubtedly, are volcanic. Their walls are similar to those of meteoritic craters: with a sharp crest and a gentle external slope, but there is no radial flow formation on them; there are only weak tangential furrows, and there are no swarms of secondary craters.

Concentric structures are visible near Shaler and Wright; near Wright and the crater north of Krasnov, there are ranges crossing over from the bottom through the crater wall over to the surrounding terrain. The crater floors are depressed. The floor of Shaler is covered with small domes; on the floor of Wright there is a central craterlet; Petit and Nicholson have central peaks of complex formation which almost fill the whole floor (similar to Focas west of Shaler).

When speaking of these craters, it must be stressed that their volcanic origin is revealed by the fresh appearance and localization by oriented pairs. If such a crater were isolated and, furthermore, if it were older, and its initial appearance were lost, it would not be discernible from the tens of other craters of similar size.

The same applies to craters of other varieties, for example, it is possible that concentric structures exist in any craters, the floor of which is overlapped by fixed covers, so that the concentric structures are buried; this crater will not differ from those of meteoritic and unknown origin.

Therefore, among craters which do not fall into endogenous forms, there must be a certain number of volcanogenic ones.



Fig. 36. Mature craters. a and b. Wright and Shaler; c and d. Petit and Nicholson. In the lower and upper parts of the frame are cordilleras of Mare Orientale. The origin of the southern cordilleras is not known: side by side with tectonic elements here, there are probably ejecta flows from Mare Orientale; the northern cordillera consist partly of volcano-like cones. Many small knolls (cinder cones?) are visible between the cordilleras. The frame width is approximately 300 km.



Fig. 37. An interpretation diagram of the craters Wright and Shaler (symbols are seen in Fig. 7).

Petal-like Craters

These are mainly nameless craters on the far side; on the near side there are Dawes, Hyginus, two craters on the east walls of Stöfler and Faraday, a crater 70 km northwest of Lansberg and others. No uniformity has been noted in the arrangement of these features, although sometimes they are localized in "clusters." But in appearance they differ from the main mass of craters of the same size, and, if one considers the latter to be meteoritic ones, petal-like craters ought to have been formed in another way (Fig. 38).

/98

A typical size for petal-like craters is 15-20 km, sometimes smaller (up to 5-10 km) or larger (up to 30 km). The external slopes of the wall are narrow -- 3-5 km, sometimes up to 1 km--and are slightly raised above the surrounding terrain; their surface is smooth and preserves the relief features of the terrain adjoining the crater; obviously in the last case the depth of the walls is relatively small; sometimes the walls are hardly discernable. The absence of a wide mantle of ejecta and ray systems, and even external



Fig. 38. Petal-like craters. A. A crater at 13°S latitude, 174°W longitude, diameter 25 km; the smooth external slopes merge inconspicuously with the surrounding terrain. B. A crater at 16.5°S latitude, 164°W longitude, 20 km along the major axis; the narrow external slopes of the wall are visible. C. Daniell, 30 km along the major axis; at the bottom there are concentric fissures.

slopes indicates that these forms are not of an explosive origin.

The internal slopes are very steep and even, without terraces and any subsidence, the floors are flat and are lower than the level of the surrounding area; in some craters there are smooth central peaks which may fill the whole floor. /99

The outlines of these craters are most characteristic in plan (Fig. 39). Some of them are polygonal; there are forms which are almost triangular. Normally there is subsidence of part of the wall inside the crater on one edge or in some segments of the crest, so that festoons, as it were, or petals protrude from the general wall contour; then the crater has the contour of a camshaft or a flower with overlapping petals. The wall crests of these craters are very fresh. Apparently, this is the result of relatively recent subsidences of the internal part of the crater, including part of the wall. The outlines of the bottoms repeat those of the wall, and the cross section of the internal slopes of the wall in the horizontal plane between the bottom and the ridge crest would have the same contours: normally there is no such conformity in craters of other types, since the angles of the internal slopes are less constant for one and the same crater.

Dawes. Diameter 18 km. The crater was described by J. R. Donaldson (1969) as a caldera. It is situated on a dome-shaped elevation (lava shield?), has low walls, which are not typical of impact forms, and characteristic outlines and profiles. On large-scale photographs, one can see that its floor is made up of slabs of matter, which have, as it were, slipped from the sides and overlap each other. But if these were slides, similar structures ought to have been seen in all terraced craters (of course, if they are not overlapped with subsequent lava). Since structures of this type on the floor of Dawes are unique, they should not be considered as landslides. Apparently, this structure was formed by a combination of viscous lava flows and subconcentric faults on the bottom.

The map only shows the most characteristic petal-like craters. /100
Apparently, among craters of indeterminate origin there should be similar formations, the profiles and shape of which should not differ so much from the shape and profile of impact structures.

A nameless crater. Size 12 x 17 km, at 26°S latitude, 156°E longitude. It has the shape of an almost regular parallelogram (see Fig. 23) and it is quite improbable that this formation was caused by impact. The floor is filled with domes and ranges 2-3 km in diameter, the wall in the south almost disappears, and, in the southeast corner, there is a small "festoon." The west wall is covered by a volcano approximately 8 km across (the



Fig. 39. Outlines and structures of petal-like and explosive craters. A. Petal-like craters: wall crests of an irregular form; outlines of the floor normally repeat those of the walls, faults and volcanoes are seen on the floor. B. Explosive craters with flat floors: the outlines differ little from round ones, there are no volcanoes; 1. internal slopes; 2. flat floors; 3. volcanoes; 4. wall crest; 5. faults. The scale is approximate, since interpretation was done using frames with a somewhat different enlargement.

central peak of Barbier) and, judging by the direction of the explosive deposits, there is another eruptive center on the site of the crater itself.

A similar rectangular, but smaller crater lies at 35°N latitude, 42°W longitude (6 x 8 km). The crater has hardly any walls, and this, so to speak, is subsidence in pure form, complicated only by three volcanic forms on the bottom.

The craters from which the so-called rills -- sinuous furrows on the mare surface -- begin are similar to the latter variety. These furrows are now interpreted either as drainage channels (roof collapses after devastation of the lave "tube" in the body of the flow), or as traces of water flows supplied from a layer of permafrost. However, the sinuous rills have transient varieties to direct fissures and connect with them; these and others in some cases intersect the remnants of the antemare substratum (the region near the Prinz crater) or are mutually intersected with short rectilinear basins (in the same place); the direction of the sinuous furrows does not always correspond to that of the slope of the terrain (a furrow which reverses its direction in the back part of the Apennines). Finally, the largest rille-shaped furrow, Schröter's Valley is surrounded by wide, even terraces, beyond which begins the more rugged relief of the Aristarchus plateau. On the floor of the valley, near one side, a fissure can be traced with several craters and volcanic cones. One has the impression that Schröter's Valley passes, at least partially, along a separation which has been exposed in three stages: the sides of terraces, the valley itself and the fissure on the valley floor. In any case, the size of Schröter's Valley does not allow it to be considered a drainage valley. The same arguments, especially the intersection of remnants of the base by sinuous furrows, can also be put forward against the water-erosive hypothesis of their origin. Apart from this, the latter needs a much deeper (up to hundreds of meters) detrital layer, which does not correspond to all known data. It is possible that rilles could be tension cracks into which basalts from the upper layer have collapsed and the bottoms of which have been filled by younger basalts. But, in any case, craters at the top part of the sinuous furrows were undoubtedly formed not by impact, but by some internal forces; judging from the absence of walls, they ought to be collapse depressions.

/101

Complex Cirques

/102

The word "cirques" is used for these structures not only because of their size and appearance (large plains, surrounded by ring walls), but also because their complex ring walls could not have been formed during ejection from the centers of the plains. In this way they differ from craters whose walls, at least partially, are formed by material ejected from the crater itself. The best features of this type are shown in Schiller and in the Ptolamaeus-Walter chain of cirques (Fig. 40). In this chain are: Ptolamaeus -- diameter 150 km; Alphonsus -- 120; Azarchel -- 105; Purbach -- 120; Regiomontanus -- 120; Walter -- 120 km. The chain extends almost along the meridian, at a steep angle to the direction of the predominant northwest faults. The submeridional edge of Mare Nubium passes parallel to the chain to the west. Here, there is in the mare a series of

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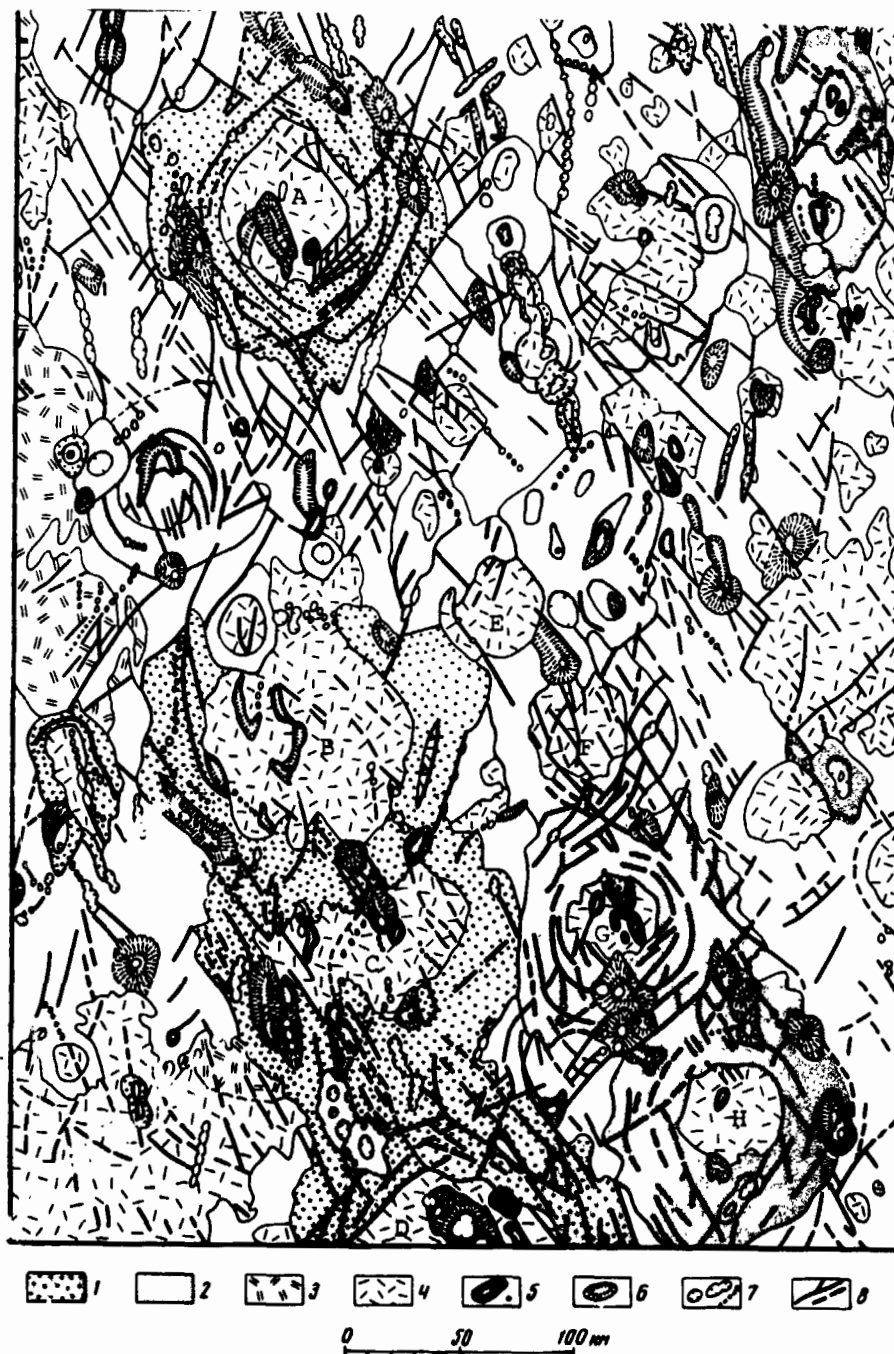


Fig. 40. Complex cirques on the highlands east of Mare Nubium. A. Arzachel; B. Purbach; C. Regiomontanus; D. Walter; E. Lacaille; F. Blanchinus; G. Werner; H. Aliacensis; 1. calderas and ring complexes (walls); 2. suggested calderas and ring complexes; 3. dark maria; 4. light (old) maria; 5. volcanoes; 6. suggested volcanoes; 7. endogenous craterlets; 8. faults.

separate, round basins: 15°S latitude, 9°W longitude, diameter 220 km; 220°S latitude, 8°W longitude, diameter 240 km; and an old mare basin Delambre, diameter 210 km. This series is oriented parallel to the Ptolemaeus-Walter chain and is older than the latter.

From the east, parallel to the axis of the Purbach-Walter chain, there is a series of smaller craters which, on the other hand, are younger than Purbach-Walter (Lacaille -- diameter 65 km, Blanchinus -- 70, Werner -- 70, Aliacensis -- 80 km). It is interesting that the basins of the western series, on an average, are 1.8 times greater than the six of the chain described, and the latter are 1.7 times greater than craters of the eastern series.

East of the Ptolemaeus-Walter chain, the terrain is badly "submerged" by old maria, and in this way this chain is situated on a submeridional anticline between two depressions.

Craters in this chain are not merely found near each other, but are closely connected by common structures into two links. This interrelationship leaves no doubt as to the endogenous nature of the whole chain.

Ptolemaeus. This cirque is a regular hexahedron. Its west and east sides are parallel to the predominant direction of faults in the area; the east side is continued by the furrow of Gylden, and the west breaches the Alphonsus wall and is directly continued by the central crest of the latter. The northwest and southeast sides are also controlled by a system of faults, interpreted using stereopairs. Faults which control the southeast side simultaneously limit the Albategnius cirque from the northwest. The northeast boundary is continued by a straight chain of closely adjoining 3-5-km craterlets. The fault on which they lie is also the northeast boundary of Albategnius. The southwest side forms a common neck with Alphonsus and, probably, is somewhat overlapped by the wall of the latter.

The walls of Ptolemaeus are broken by numerous faults, and their initial structure is not preserved. However, two domes with summit craterlets are visible on the east wall, and are similar to volcanoes; the west wall (continuing the central ridge of Alphonsus) consists of a series of prolate knolls arranged in a link fashion; they could be tectonic blocks or extrusive bodies; in any case, here there is no hint as to the structure of the "ejecta from the center" of the cirque.

Undoubtedly, the floor of Ptolemaeus is covered by lava, on the surface of the floor there are remains of buried ranges and craters; and faults, cutting the wall disappear on the floor, that is, they are overlapped.

A considerable number of small craterlets on the floor of Ptolemaeus are not impact ones but endogenous formations (Fielder, Marcus, 1967). /104

Alphonsus. In comparison with Ptolemaeus, this cirque has a more rounded form (probably because of the cirque's smaller size? Therefore, that is probably why Azarchel, the smallest cirque of this chain is most rounded?).

However, the west and east walls of Alphonsus are linked with large faults which leave them at a tangent. Here, traces of the east fault continue farther to the floor of Ptolemaeus, which shows the prolonged effect of these faults.

The wall of Alphonsus is similar to that of Ptolemaeus. In places it consists of merging rounded ranges and knolls, and in one case it can be seen (Firsoff, 1967a) that several of these knolls divide part of the lava floor on the edge of the cirque, and a "lake" or "lagoon" is formed. Consequently, knolls superimposed on the floor of the cirque are also volcanogenic. This conclusion is confirmed by the smooth nature of details within the wall and the small density of craterlets on the wall. Obviously, the small structures and craterlets are overlapped by some material, the only source of which could be volcanism. Obviously, the detrition of small structures during slumping wash does not explain what is observed: individual craterlets are well preserved on slopes, and the relief on horizontal sections of the wall is the same as on slopes.

Two lava lakes are clearly visible on the west wall, and are bounded by terrace-forming faults. Both of them lie high above the bottom and above the surrounding terrain.

The central crest has the same features as the wall. In the north it becomes the Ptolemaeus wall and in the south merges at a tangent with the wall of Azarchel. The central peak shows signs of superposition on the rocks of the ridge. Observations of gas emanations in the region of the central peak are well known (Kozyrev, 1963), but besides them red luminescence was also noted here (Moor, 1965).

The bottom of the cirque, photographed by Ranger 8 reveals many details of volcanic relief (Ranger 8 and 9, 1966): volcanoes, craterlets with dark aureoles, etc.

Here there are dimple craters, craterlet chains, and craterlets on fissures (volcanic vents). The overall number of craterlets over a unit of area of the floor is 1.5-2 times as many as on the wall of Alphonsus, although the floor, undoubtedly, is younger than these walls (Hartmann, 1967b). Here, there is a considerable abundance of craterlets in a range of the first few kilometers, which can only be explained by volcanism.

Subconcentric and radiating cracks, extending to several tens of kilometers, are also visible on the floor. These cracks could hardly have been caused by compression of cooling lava flows on the surface, rather they reflect compression of deeper volumes of matter, which behave as one body for the whole cirque (magmatic focus). Furthermore, a fissure on the floor near the east side of Alphonsus can be traced through its north wall and later passes along the west side of Ptolemaeus, where several craters are seen on it, which indicates a deep-lying fault.

Alphonsus is smaller and younger than Ptolemaeus, and, in its turns, Azarchel is smaller and younger than Alphonsus.

Azarchel. This is the youngest, smallest and roundest cirque in the whole chain. Apparently, its roundness and well-preserved nature is explained by the fact that it occurred after the basic movements along the Imbrium fault and was hardly moved by them; it also occurred after the main period of Altaic submersion. As a result, the structure of the external slope of the wall is quite well preserved, and several conclusions can be made on the nature of the flow form of large craters on an example of this cirque. A conclusion on the volcanic origin of Azarchel is not only based on its position in the chain of similar cirques. As has already been said, the central volcanic ridge of Alphonsus, continuing to the south, merges at a tangent with the wall of Azarchel. Several clear furrows extend parallel to it, also entering the concentric faults of the wall of Azarchel at a tangent. Generally, faults around Azarchel are oriented predominantly to the northwest and northeast, at an acute angle or at a tangent to the adjoining segments of the wall crest. On the north and south walls, that is, along the axis of the cirque chain, the faults form a characteristic "gothic structure."

/105

The structure of the western sector of the external slope of the wall is similar to a smooth-radial flow form, which is thought to be one of the main indications of the crater's impact origin; it is suggested that it was formed by streams of matter ejected from the crater when an asteroid exploded. However, on close examination it appears that if these "streams" also merge towards one center, it is not in the center of Azarchel, but on its west wall, where it can be assumed there are volcanic vents. Furthermore, some of these subparallel "streams" pass at a tangent to the wall and are even tangential when they do not touch the side of it.

As opposed to meteorite craters, where the external slopes of the walls gradually fall as they leave the crater, in Azarchel the wall is divided into two parts: strictly, the wall is a massive internal ring with steep external slopes, and the external sphere of the wall is a belt of ridged and furrowed

relief. The transition from the external sphere to the internal wall is marked by a clear-cut scarp.

The internal slopes are terraced by numerous subconcentric faults. The flat (undoubtedly lava) floor is fringed with concentric tension cracks which sometimes turn into terrace-forming faults. These transitions mean that the terraces were not formed by slides, but by faults.

The central peak extends along the axis of the chain and is continued up to the side of the crater as a poorly expressed crest.

Purbach, Regiomontanus and Walter. These cirques are similar to Alphonsus. Their central peaks are also extended along the axis of the crater chain; however, in Purbach the central peak consists of several semiarcs -- either these are relicts of submerged volcanic craters or they are extrusives. There is another interesting detail in Purbach: the northwest sector of its wall is a flat-topped platform approximately 15 km wide, fringed on all sides by subsidences; it is possible that this is a shield volcano of the wall or a relict of the initial terrain.

The walls of these cirques are interconnected by diagonal faults which pass at a tangent from one wall of one cirque to that of the other, where they merge with concentric faults.

Schiller. The cirque has been classified as an endogenous structure due to its remarkable shape, and also by its position along the ridge of a large concentric thalassoid. The central ridge, which passes along the axis of this crest along the floor of the circle in the northwest, is of course volcanic -- rather like a large dike which has emerged on the surface. (A similar dike is visible in a double merged crater on the far side, at 16-20°N latitude, 174°E longitude. Here, it is in the articulation zone of both craters, passing from one to the other along a line joining their centers.)

The structure of Schiller is similar to a structure of the cirques described. /106

To this variety belong the groups Cavalerius-Hevelius-Lohrmann, Humboldt-Hecataeus, Olbers-Hedin-Riccioli, and a complex structure between 20 and 30°S latitude at 155°W longitude and others.

Explosive Craters (Craterlets)

As opposed to large craters, the formation of which is extremely varied, most small craters -- craterlets (of a range of hundreds of meters or kilometers) -- are very similar to each other and only vary by the degree to which they have been eroded.

Therefore, volcanic craters of this size can normally only be identified by their mutual disposition, surface density and regular position in the structures determined. Volcanic craters in this range, distributed haphazardly, apparently cannot be distinguished from the large number of impact forms if there are no good photographs.

Impact craterlets grouped in chains are most easily identified³. Approximately 20 such craterlets (1-3 km) form a sublatitudinal, slightly curved chain 50 km in length in the crater Davy. There are no other such chains in the area and no other large, young crater whose ejecta could have formed this chain. Undoubtedly, these craterlets trace a fault line overlapped by mare rock on the floor of Davy.

Another chain of the same length is 100 km northwest of Gruithuisen. It passes partly along the crest of the mare ridge, and is partly a direct prolongation of it; craterlets in this chain are somewhat elongated. It is impossible to explain the formation of this chain by exogenous means.

Many craterlet chains are linked with fissures grabens and other structural lines. The Hyginus furrow is a classic example of a series of craterlets along a graben: it is closely linked with the fault system of the adjoining area, and the craterlets along it are quite different from those normally thought to be impact ones (almost indiscernible walls, the absence of secondary hollows and the elongation of craterlets).

Craterlets of the submeridional chain 100 km northeast of Copernicus are so interlinked that they form a single volcanic trench, replaced to the north by a mare ridge of the same directionality.

A short craterlet chain near the northeast rim of Ptolemaeus, at first glance, is not linked with faults. But study using stereopairs and photographs taken during different lighting indicates that this chain lies on a structural line linking the northeast walls of Ptolemaeus and Albategnius.

Sometimes the link between craterlet chains and tectonics is observed during statistical analysis of their directions and frequencies (Fielder, Marcus, 1967; Fielder, 1968; Fryer, 1968).

³ As yet it is not clear whether this should be a chain or a random accumulation of craterlets, and, furthermore, how to distinguish an endogenous chain in an unclear case. Therefore, here we are speaking of the most obvious and indisputable cases -- when isolated chains are not linked to presumably impact structures and, when around them, craterlets of similar in size to craterlets of the chain are rare.

There are many such examples. The lower dimensional limit of endogenous craters in chains is 300-700 m; the largest craters of simple formation, joined in a chain, attain 20-30 km. The map only shows those chains in which the crater size is, on an average, 3-10 km; smaller chains are shown as faults, and deviations from the simple cup-shaped form are normally seen in the largest craters -- a flat floor, subsidences, irregular shape, -- which enables them to be classified as nonexplosive forms. /107

Many craterlet chains not shown on the map can also have an endogenous origin. They are not shown since it is difficult to distinguish them from chains of secondary impact craterlets. Hence, in a gothic structure on the northern fringe of the crater Philolaus, many chains are oriented in a northwestern and northeastern direction and closely linked with faults in the same direction; one can be assured that these chains are endogenous. But what of chains radial to Philolaus? On one hand, they are similar to secondary impact formations; but, on the other hand, there are chains with a direction which is intermediate between tangential (endogenous) and radial chains; therefore, it is possible that some of the radial chains should also be shown as endogenous.

Subsidence belts around Mare Orientale are furrowed with numerous craterlets, knolls, fissures and chains, which are similar to ejecta fields around large young craters. But this is not ejecta from Mare Orientale, even if one accepts its impact origin: in fact, rocks in subsidence belts overlap the concentric structure of the cordilleras with its coarse radiating "ejecta", and this means they were formed later. Therefore, subsidence belts should consist of extensive volcanic fields and a craterlet chain in them, just as many individual craterlets appeared as the result of areal volcanism. It cannot be ruled out that those deposits which were thought to be ejecta from large craters could also partially be volcanic accumulations, and some craterlets in them could be of an endogenous nature.

Craterlets on central peaks, isolated volcanoes and domes are normally too small to be shown on the map. They only reach a size of several kilometers in exceptional cases. The number of such craterlets after photography, carried out by space vehicles, was too large to explain them by a random process.

Of the huge number of small craters chaotically strewn over the whole lunar surface, most are probably of impact origin. But in some cases the endogenous nature of these craterlets can be determined.

The increased density of craterlets on the floor of Alphonsus in comparison with its walls apparently can be explained by the presence here of sinkholes (dimple craters) and volcanic vents, some of which are identified by dark aureoles and by their links with fissures (Firsoff, 1967a; Hartmann, 1967b;

Chapman, 1968). In one of the cirques on the far side of the Moon, a lava flow was observed on the surface of which there were more craterlets than on the area overlapped by it; obviously, among them are gas explosive craters or subsidence craters (Hixon, 1968). The elongation of craterlets in some regions agrees with the tectonics of the area, but is not linked with the ejecta from large craters (Warner, 1962; Fielder, 1961). Sometimes mutual intersections of craterlet walls are visible which show the prolonged formation of one or both craterlets: for example, at 7°S latitude, 143°W longitude, the diameters of craterlets are 10 and 12 km, or a pair at 48.5°N latitude, 5°W longitude, with diameters of 6 and 4 km. Dark aureoles of fine material are sometimes seen around some craterlets; these should be considered as volcanic (Salisbury et al., 1968). But a volcanic system can eject not only dark ash, but light material, that is, some craterlets with light haloes can be endogenous. Incidentally, /108 most volcanic craters, distinguished by their structural position, do not have dark aureoles.

Some estimation of the relative age of different lunar formations showed that old maria regions (Altaic) are comparatively little older than dark maria (Pohn, Offield, 1970). But the density of craterlets on Altaic areas is several times greater than in the dark maria; since both of these are of similar age, this abundance can be partly explained by volcanism.

Finally, there are groups of small craters (for example, at 30°S latitude, 116°E longitude) which are clearly determined by their similar size and close disposition on a background of relatively infrequent craterlets of different dimensions in the surrounding area; apparently, these can be compared with maar fields on Earth.

The simple cup-shaped form of most craterlets indicates their explosive origin; apparently, some craterlets without walls are subsidence forms. The dimensions of the smallest of them are comparable with those of terrestrial craters with a diameter up to 3 km. The appearance of larger explosive craterlets is apparently linked with the specifics of lunar volcanism. Judging by some signs, subsidences, covered by subsequent eruptions, helped to form craterlets with diameters from 10 to 20 km and above.

Impact Craters

The number of meteorites falling on one unit of area of the Moon over a certain time interval varies little from the number of meteors and meteorites which fall over a similar area of the Earth during the same time. But bodies with a mass less than $5 \cdot 10^8$ g lose a considerable part of their mass and velocity when passing through the Earth's atmosphere; they often brake to a

free-fall velocity or disintegrate without causing large craters. Any bodies which fall onto the Moon cut into it with a compact mass and a high velocity. Erosion and sedimentation are continually erasing meteorite craters from the face of the Earth. Apparently, on the Moon, craters in the kilometer range are preserved for hundreds of millions of years, unless they are overlapped by volcanic covers or new craters (Ross, 1968). Whereas on Earth there are several tens of large meteorite craters, on the Moon this number must be many times greater.

Apparently, in the antemare period the meteorite flux was much greater than today (the post-accretion stage) and a considerable number of craters formed then should be preserved until today (Hartmann, 1967d; and others).

In this way, the Moon is covered with volcanic and meteorite craters. When analyzing volcanic forms, for comparison we must indicate those craters which we believe to be primary meteoritic.

The main indications of a meteorite crater, apparently, must be the elongated ray systems, the swarms of secondary craterlets and the flow-like and dune relief of the external slopes of the wall, and also large blocks strewn around the crater.

1. Ray systems. The mean velocities of volcanic ejecta during eruptions do not exceed 100-200 m/sec, and during catastrophic, directed explosions -- 300-500 m/sec (Ritman, 1964; Markhinin, 1967; Kirsanov, 1968; Gorshkov, Dubik, 1969; and others). In lunar conditions the maximum distance of ejection at such velocities is 5-25 and 60-170 km, respectively. In plan, ejecta from normal eruptions are distributed more or less evenly, and deposits of directed explosions -- over relatively narrow sectors. The first case corresponds to craterlets with dark aureoles on the bottom of Alphonsus, the ejection velocity from which was estimated to be on the order of 100 m/sec (Ranger 8 and 9, 1966); the second type is represented by a ray of the Messier crater, approximately 170 km in length. /109

Possibly, during individual, more powerful explosions, the ejection velocities exceed these values; however, these will be exceptions. Lunar ray systems are a widely distributed rule, and typical ejection speeds, and not exceptional ones, should be compared with them.

Hence, it follows that isometric ray systems more than 25 km in length could scarcely be of volcanic origin, even if one does not assume that they were formed by series of directed explosions, oriented over all countries of the Earth. Longer ray systems obviously were formed during meteorite impacts, and craters with ray systems stretching for hundreds of kilometers, undoubtedly, are primary meteoritic.

2. Secondary craterlets. Strewn around ray craters at a distance of up to 300 km and above, these craterlets group together in rays and in the head sections of individual ray elements, and reach a size of several kilometers. Impact masses on the order of 10-100 million tons are required to form these (Stanyukovich, Bronshteyn, 1960; Ranger 7, 1965), and the largest blocks, ejected during catastrophic eruptions have masses of thousands of tons, possibly up to 50 thousand tons (Gorshkov, Dubik, 1969; Yermakov, 1969b). Such craterlets (with rays directed from the main crater) can only be formed when large fragments fall after a meteorite explodes.

3. Flow-like and dune relief. This relief, seen on the external slopes of craters, is formed by interlaced ranges, furrows, knolls and holes, similar to the relief of sediments of underground nuclear explosions; the impression is created that it was formed by some "streams" or "braids" of matter, ejected from the crater (Fig. 41). As it moves away from the crater, this relief gradually levels out and disappears, becoming the ray systems. The better developed the ray systems are, the more sharply expressed is the stream-like relief; at the same time, there is normally no such relief among volcanogenic craters, identified

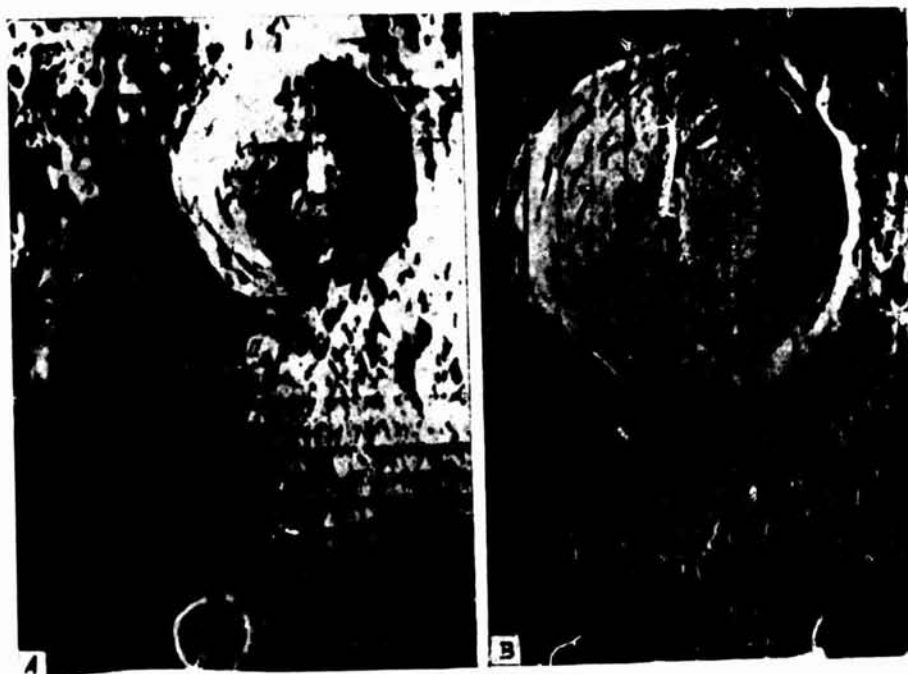


Fig. 41. Craters with stream-like structures.
A. Monder (Mare Orientale), diameter 55 km; a volcano (a) is visible on the south crest of the wall;
B. Aristarchus, diameter 40 km.

by structure and position. There is some similarity to the stream-like relief in individual volcanic regions (Mare Orientale, the floor of Copernicus, and the floor of Pythagorus), but there is no complete analogy (Fig. 42). Therefore, a typical stream-like relief (Copernicus, Aristillus, Aristoteles) can be an indication of the meteoritic origin of the crater.

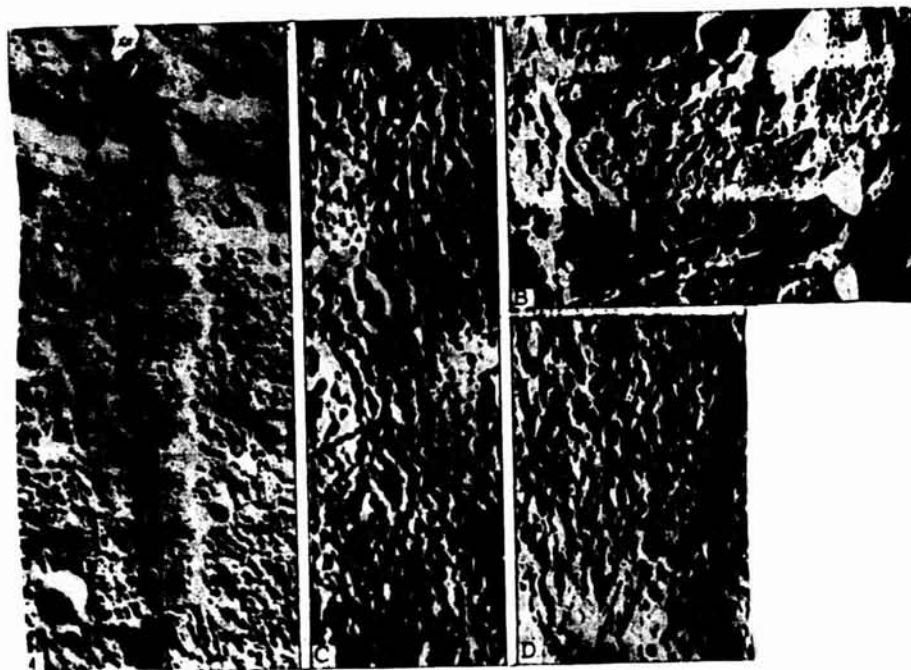


Fig. 42. Structures similar to stream-like systems. A. The Alpine Valley, 100 km in length. The area is covered with furrows and craterlet chains which should not be considered as impact, since northwestern directions are traced on the youngest floor of the valley. B. Part of the crater floor of Pythagorus; furrows and ridges, similar to stream-like activity, extend from the central peak along the floor, but are of endogenous origin; the frame width is approximately 90 km. C. Part of the crater floor of Copernicus: a volcanic field, similar in structure to fields of secondary impact craters; the frame width is approximately 3 km. D. A section of the highland north of the crater Tycho. An arrow indicates the direction toward the center of Tycho; the frame width is approximately 20 km. It can be considered that this relief was formed when fragments fell after an explosion which created Tycho; obviously there is a similarity between this structure and that of the volcanic floor of Copernicus.

4. Large blocks. Very large fragments are thrown from a crater when a meteorite explodes. But they are only discernible around relatively young craters and only on large-scale photographs. Their dimensions (up to tens and hundreds of meters) cannot be explained by volcanism.

Apparently, now one must not separate all volcanogenic structures on the external slopes of flow craters from ejecta structures, since they look very similar. For example, the crater Gould (east of Bullialdus) is intersected by a 80-km craterlet furrow. It is oriented obliquely to ejecta from Bullialdus and, undoubtedly, is endogenous. The southwest end of the furrow is continued south as a 40-km craterlet chain, subconcentric to Bullialdus. If the first crater had been radial to this one, the second would have been closer to it in the ejecta sphere, and they would not be discernible from the impact chains. /110

Similarly, southeast of Eratosthenes, 25 km from its crest, there is a concentric chain of blurred craterlets, which could be considered as impact if it had not continued north in the form of a fault scarp.

Indications of impact origin are expressed to a different degree in craters of different size. Craters less than 20 km sometimes have isometric ray aureoles with a ray length of up to 30-80 km (Darney, 15 km; Cyrillus A, 15 km) or a dune relief and swarms of secondary craterlets (Mösting C, 4 km).

One can sometimes see that traces of stratification of the substratum on the internal slopes of a crater are somewhat elevated relative to the surrounding terrain. All these craters have a cup shape with a wall width of 0.2-0.5 crater diameter, they have no terraces or central peaks, and, on small-scale photographs, are indistinguishable from volcanogenic craterlets and from the large numbers of craterlets without determined genetic signs. The latter are distributed completely chaotically, and their density is no more than the mean "background" density on "frequency-diameter" curves, which are, obviously, distribution functions of meteorites according to mass and frequency. Therefore, most craterlets with a diameter less than 10-20 km are almost certainly meteoritic ones.

Near meteorite craters with a diameter of approximately 25 km and above, there are often elongated rays and, at the same time, there are central peaks. Near Menelaus (25 km), the rays reach a length of 150 km, and near Lalande (25 km), they reach 200 km, and, inside, there is a central peak and terrace. It is thought that ray systems which are not steep or do not form a compact cover are eroded with time and disappear or are covered with a thin layer of volcanic products. Therefore there initially were rays near a much larger number of craters than can be seen today. /111

For example, near Ross (25 km), rays, which were apparently overlapped with subsequent mare covers, manifest signs of flow activity normally associated with rays on the north slope of the wall.

A typical flow diagram of the external slopes of a wall appears in craters with a diameter of approximately 30 km and above. A weak flow form and also a central peak and a terrace are visible near Delisle (26 km) and Harding (28 km); here there are also two terraces and small rays. Near Euler (30 km) the flow form is clearly expressed, with signs of a gothic structure; there is also a flat floor with a central peak and two terraces. /112

Well preserved craters with diameters of approximately 30 km can be divided according to morphology into meteorite and volcanic ones even on medium-scale photographs. Hence, 30-km craters listed above differ considerably from a crater of the same size in Mare Orientale at 4°S latitude, 92°W longitude with its large central peak, two volcanoes on the wall and smooth internal slopes. Two hundred km southwest of Harding lies a similar crater of the same size, but its walls are smooth, with internal concentric scarps; there are no swarms of secondary craterlets, the crest of the wall is overlapped by a volcano and a ridge system is visible on the bottom.

Rays, the flow forms and swarms of secondary craterlets are expressed maximally in craters with a diameter above 40 km. They are visible best in craters on flat mare surfaces: Autolycus (40 km), Aristillus (55 km), Copernicus (90 km, rays up to 600 km) and are seen least frequently in highland forms: Tycho (90 km, rays up to 1500 km), Pythagorus (100 km). The wall structure of larger ring forms is caused to a considerable extent by tectonic and volcanic manifestations; signs of meteorite impact are scarcely visible in them (Humboldt, Tsiolkovsky).

Simultaneously with signs of meteorite impact in craters larger than 40 km, traces of volcanic activity are widely represented: flat floor; complex central peaks; volcanoes on the floor and on the walls; and craterlet chains along the faults of the external slopes of the wall. The three best known meteorite craters reworked by volcanism are:

Aristarchus. Diameter 40 km. The age of the crater is based on calculating the density of craterlets and is approximately 60-100 million years; but this is not the time when the crater itself was formed, but only the age of those sections of the surface for which calculations have been made. There are traces of volcanic activity on the floor and walls of Aristarchus; therefore, the initial relief of the crater in places is overlapped by younger volcanic rocks and, apparently, the crater itself is more ancient than the estimated sections. On the other

hand, it is not known how many craterlets appeared as a result of this volcanism; if they are not included in the calculations, the surface is younger. Finally, numerous observations of luminous patches in Aristarchus and its vicinity show the present-day volcanic activity in the region (Moor, 1965; Kozyrev, 1963; Hartmann, 1968).



Fig. 43. Part of the crater floor of Aristarchus. 1. Volcano; 2. sections with a softened relief; 3. smooth sections (ashes?); 4. a flow on the slope of the wall; 5. craterlets; 6. faults; 7. the boundary of the crater bottom. Frame width 4 km.

The crater floor is a compact volcanic field (Fig. 43). It is covered with furrows and fissures of several systems and strewn with light, smoothed knolls. Some of these knolls have summit craterlets, and many overlap bottom fissures; obviously, all these are cinder cones. Individual, even "flows" are visible, and are superimposed on faults. An elongated central peak apparently consists of two volcanoes. In the northeast angle of the floor is a 7-km ring wall, clearly distinct from the impact crater walls.

The internal slopes are furrowed by radial furrows and concentric terraces. On the terraces there are lava lakes with characteristic cracking of the surface, which indicates the deep-lying nature of the terrace-forming faults. Radial furrows may be partly formed by traces of blocks which have rolled down, and partly by relicts of the initial ejecta diagram. It is possible that some radial furrows appeared when large blocks slid

over the slope. But some of these furrows mark faults: they deviate from radial directions, pass from the internal slope of the wall to the external one, and branch out; as the furrow extends, it is replaced by crests and craterlet chains, and fault displacements are visible along them.

The external slope of the wall can be roughly divided into three zones.

The internal zone, up to 20 km in width, is characterized by relatively smooth relief, and this smooth material is overlapped by the flow relief of the following zone. In the southeast it can be seen that the internal zone is dissected by faults radial and concentric to the crater, and the faults are overlapped by patches of lava and volcanic domes. Gothic structures are clearly visible in the north and south. /113

The middle zone, 30-40 km in width, is flow-like and formed nonuniformly in different sectors. Basically, it is covered by densely lying clusters and chains of craterlets measuring from hundreds of meters to 1-2 km, subradial to Aristarchus. These are probably traces of initial ejection. But in the south the craterlets reach a size of 2-4 km, and the direction of their walls is closely linked with that of gothic faults; tongues of some material, similar to lava flows, extend from those craterlets open to the south; their dimensions are approximately 2-3 by 10-12 km. A characteristic diagram of the northern sector of the middle zone forces one to assume that the flows here are like those near Tycho, in the region where Surveyor 7 landed. Incidentally, the elevated northern sector is clearly separated from the gently sloping external zone by a rille-shaped furrow; possibly, this is linked with the tectonic elevation of the middle zone.

The external zone is a region of dispersed ejecta, small indentations and rays extending 200-300 km from the ridge of Aristarchus. It is the dimensions of these indentations, up to 0.5-1 km, and the length of rays which show that the crater has impact forms. After Aristarchus was formed, its diameter increased by about 1 1/2 times due to the subsidence of the sides. In this way, the crater and the surrounding area within a radius of 20-40 km underwent volcanic reworking.

Copernicus. Diameter 95 km. The crater's age has been estimated to be 300-600 million years (with the same reservations as for Aristarchus).

Obviously, Copernicus is a meteorite crater. Otherwise, it would be difficult to explain the length of its rays, up to 500-600 km, and the wide distribution of craterlets clusters, small ranges and knolls around Copernicus. (Two-kilometer rays are strewn within a radius of up to 200-250 km from the crater's center).

It is true that one of the longest rays, passing between Lambert and Timocharis, is directed not from Copernicus, but from a region 50-70 km east of it, where the volcanic furrow of Stadius and submeridional gently sloping scarp lie on its prolongation; the ray itself passes partly along the meridional segments of mare ridges. If one traces the direction of individual components of its ray elements, they would again be oriented not towards Copernicus, but towards a region 100 km west of it. It is difficult to understand how this ray could have been formed by ejection from Copernicus; however, as yet there is no satisfactory alternative to this explanation. /114

Some of the small knolls in the vicinity of Copernicus are indistinguishable from ejecta on telescopic photographs, but in fact, are volcanic formations. There are just as many craterlets which are not secondary impact ones as there are volcanic ones: they have dark haloes, sometimes are polygonal, extended tangentially towards Copernicus (Warner, 1962), many have no rays or directed ejecta (Schmitt et al., 1967).

Obviously, the crater bottom is composed of volcanic rocks. Here individual volcanoes are visible, as are clusters of cinder cones, cracks and rilles, which on some segments are overlapped by volcanic covers. A central peak disintegrates into dozens of volcanoes with a diameter of up to 5 km, with summit craterlets, sommas, craters open at one side and dikes. It is remarkable that the structure of some parts of this purely volcanic field is similar to the structure of "ejecta" on the external slope of the wall (see Fig. 42).

The internal slopes are terraced, and lava lakes are seen in the rear sections of the terraces. A lava flow running down the slope from one of these lakes is clearly visible; similar structures are also seen in other sections of the internal slopes. An interesting question relative to the morphology of lava and its composition is linked with the structure of this flow. As far as one can judge, the lava in the lake lies horizontally and quietly; lava flowing from the lake down the slope and having, obviously, the same composition, is characterized by its uneven, ridged relief. In this way, the morphology of lava cannot depend on its composition, but on the way in which it solidified: statically or in motion.

The terraces are intersected by radial and tangential faults, which continue partly to the external slope of the wall. On one of the photographs from the Lunar Orbiter 5, a radial fault is visible which intersects the southwest crest of the wall of Copernicus; on the crest and the upper part of the fault scarp along this fault, there are elongated craterlets with elevated rims, that is, they are not subsided, but volcanic. Consequently, this radial fault was active after the most recent subsidence of the wall.

Where the terraces are not intersected by faults and not overlapped by volcanic covers, they retain traces of the surface surrounding the initial crater; its diameter was not more than 50 km.

The external slope, as opposed to Aristarchus, is furrowed by faults in a belt 20 km wide along the crest; later, the relief becomes softer, and the faults are erased as if they had been overlapped by some incoherent material. As on the internal slope, post-fault lava lakes are encountered in sinkholes; in individual areas there are structure similar to lava flows, issuing from cinder cones. The faults fall into several systems; mainly these are radiating cracks and faults of a gothic system. The latter is expressed not only by small cracks, but by large crests in the north and south. The link between these crests and individual craterlet chains allows the latter to be considered as nonimpact although, according to their outward appearance, they do not differ at all from "ejecta" craterlets.

Finally, one must note the relatively clear-cut bend which separates the elevation of the wall of Copernicus from the external wall of ejecta (approximately 20-30 km from the crest of the wall). Apparently, this elevation is of complex origin: accumulative (meteoritic ejection and volcanic accumulations) and tectonic.

Tycho. Diameter 90 km. The age of the crater is 200 million years (with the same reservations). Undoubtedly its gigantic rays occurred during the explosion of a meteorite which formed a crater with a diameter of approximately 60 km (Figs. 44 and 45).

The floor of Tycho, which from Earth looks almost flat, on large-scale photographs is filled with countless knolls, furrows and crests. On the summits of the knolls there are craterlets and somma-shaped subsidences. This smooth dome frequently overlaps a finely-ridged, fissured base, since base faults are "set" into the dome and emerge from it on the other side; most probably these are small volcanoes.

/115

Fig. 46, on the same scale, shows the position of some volcanoes in the Gegam highlands, and Fig. 47 shows the profiles of some of these. Morphologically they are similar to the knolls in Tycho, although the undestroyed volcanoes in Armenia are larger in size and steeper. The same proportions are also seen in the Kamchatka volcanoes in comparison with the lunar ones. On small (the first hundreds of meters) knolls on the floor of Tycho, summit craterlets are sometimes also visible, but these forms are lost among the small irregularities of the ridged and furrowed terrain. Apparently, some of them should be classified as small cinder cones, others could have occurred when intersected by faults of warped lava flows or simply at the intersection of two or three linear disturbance systems.

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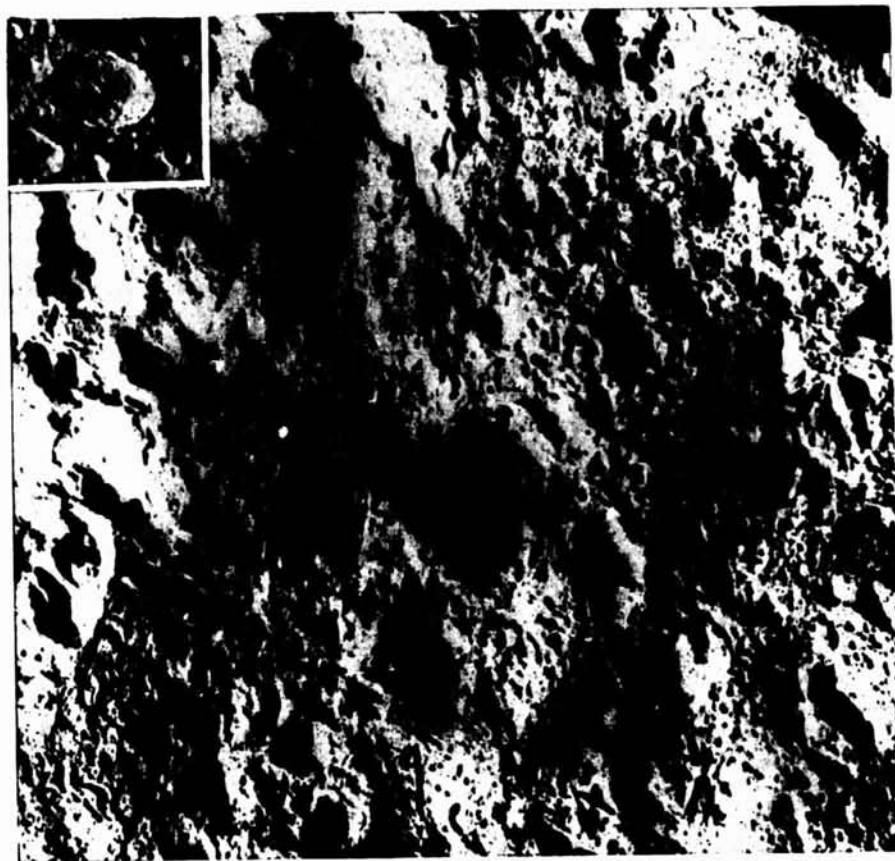


Fig. 44. Part of the floor of the crater Tycho. Frame width 24 km. To the left above is a telescopic image of the same crater.

Linear details -- furrows and crest, normally closely inter-linked -- apparently belong to two genetic varieties. The first was formed by faults which are separated along the single orientation of rectilinear structures; this orientation is traced along the whole visible section. The presence of through fault systems contradicts the idea of a finely granulated layer below the bottom of the crater, as follows from the meteoritic hypothesis: the environment must be sufficiently coherent to preserve single stress systems. Probably, the fragmentated rocks were subsequently "healed" by magma.

Linear details of the second type are apparently linked not with tectonics, but with the specific structure of lava flows. The presence of such flows is determined by the characteristic diagram on their surface. This diagram is similar to the warping structures of lava fields on Earth. It is visible best near the

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Fig. 45. An interpretation of part of the floor of Tycho (see Fig. 44): 1. lava fields with fissures and furrows; 2. smoothed sections (pyroclastic accumulations?); 3. individual lava flows; 4. volcanoes; 5. volcanic craters; 6. faults and fissures; 7. subsidences on the summits of the volcanoes; 8. the boundary between the floor and the wall; 9. the boundaries of individual structures.

side of the crater: in the bottom left corner of the frame (see Fig. 44), and also to the north, approximately in the center of the frame. Judging by the flow diagram, these flows apparently come from two depressions in the sides of Tycho open to the east. Their structure is similar to that of terrestrial andesitic and dacitic lavas.

On available photograph the structure of the internal slopes of Tycho is difficult to interpret. Only in the northern and southern sectors can one see well that the northwest and northeast faults form a lattice gothic system, the only one for the

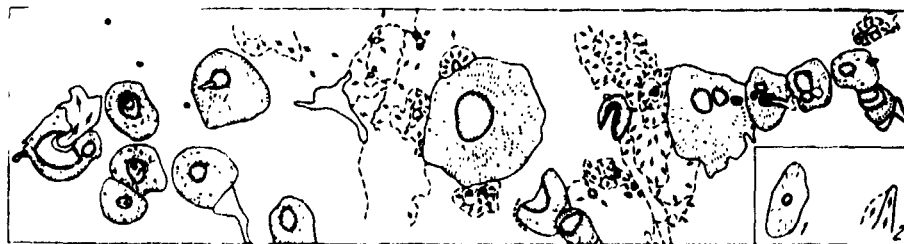


Fig. 46. Volcanoes in the Gegam highlands (Armenia) according to material by V.G. Trifonov: 1. volcanoes; 2. lava flows. The scale is the same as that on Figs. 44 and 45.

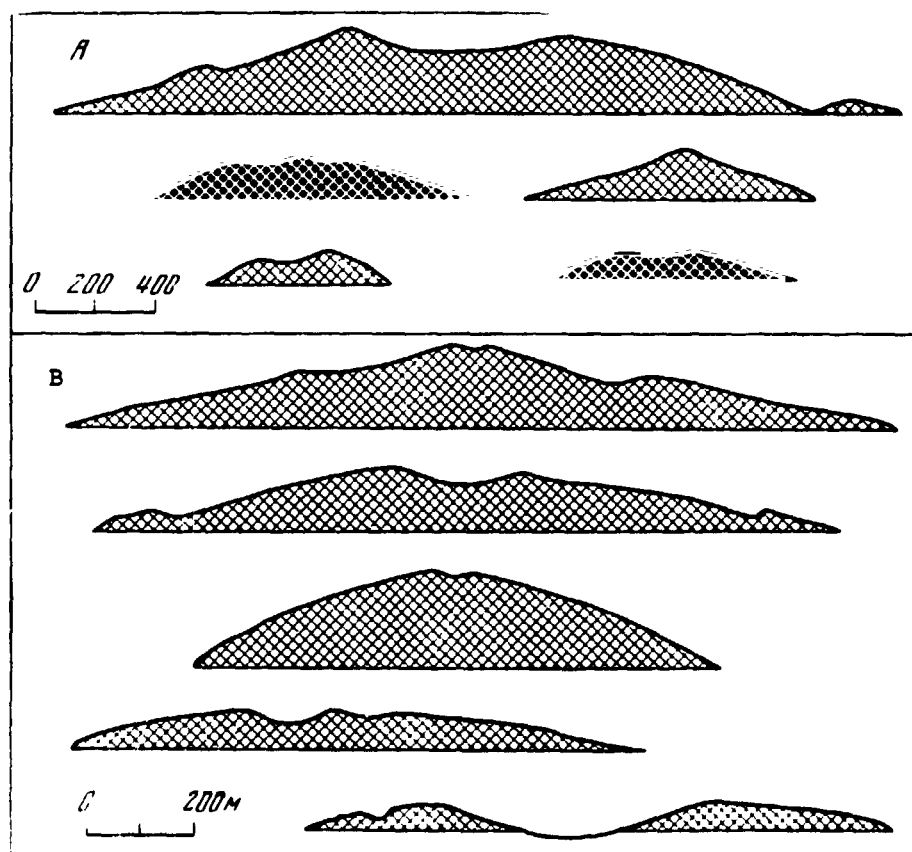


Fig. 47. Profiles of volcanoes in the Gegam highlands (a) and volcanoes on the bottom of the crater Tycho (b).

internal and external slopes of the wall. Here, one can also see individual flows and knolls similar to volcanoes.

R. G. Strom and G. Fielder (1968) interpreted some lava flows in various stages of preservation and lava lakes in holes on the external slope of the wall. On the north wall of Tycho there is a 5-km knoll with a 1.5-km crater on the summit, and in the crater there is a small central protrusion. One has the impression that the knoll is a small volcano, superimposed on the flow leaving it.

R. G. Strom and G. Fielder believe that the coarse structure of flows of the northern wall indicates the great viscosity of lavas and, consequently, a different composition in comparison with the maria. It is possible that this is so, although according to information from Surveyor 7 the only difference between the matter on the surface near the wall of Tycho and that of the mare matter is that it contains a somewhat smaller iron content. But it is more probable that the origin of the irregularities of the flow is due to "telescoping" through the flow of base faults, that is, the irregularities are subsidences and warp in the lavas which overlap the furrows, or they occurred due to secondary explosions and upheaval above fissures or are linked with the additional movements along faults, etc. In any case, the lattice faults also affect the structure of flows, controlling the boundary of their distribution and the orientation of craterlets 100 km to the north of the northern crest. This orientation is so distinct that most probably the craterlet chains here are not impact but endogenous. /116

The wall structure in the eastern section is different. Here the faults are predominantly concentric, although if the northwest and northeast structures were changed, they would be visible to the same lighting. A concentric zone of sinkholes from 8 to 15 km in width extends beyond the wall crest, bounded from the east by a second subconcentric crest, so that the wall of Tycho here has two crests with a relative subsidence zone between them. Some sinkholes are filled with a dark matter with an even surface forming "lakes." If this matter was dust, all the sinkholes should be filled uniformly; however, there are also "dry" basins. Consequently, the lakes are filled with volcanic material. Beyond the eastern boundary of the wall of Tycho, the terrain is again intersected by radial and tangential faults.

Thus, at some period crushing probably occurred along the tangential and concentric faults around the ring wall of Tycho; the fissure zone which was formed became the place where magmatic products emerged on the surface.

It must be repeated once more that available photographs do not always make it possible to reveal volcanic forms in lunar /117

craters. Hence, photography carried out during the flights of Apollo 10 and Apollo 11 made it possible to identify individual lava covers, intrusive rocks and dikes in one of the craters on the far side (40° N latitude, 120° E longitude), whereas on Orbiter photographs they are hardly visible (El-Baz, 1970).

But the undoubted fact remains that there is a wide distribution of volcanic structures in impact craters. Possibly, the floors of some craters bear traces of surface fusion, occurring when a meteorite exploded. However, this explanation is not suitable for the majority of such craters. Judging by the remains of submerged structures, lavas on the floors often occur a considerable time after deformation of the crater itself. Their volume is clearly greater than that of the melt which could have occurred at the moment of impact (even to the complete submersion of the crater of the Wargentín type). Finally, volcanic structures are linked with the terraces of internal slopes and are distributed on the crest and external slopes of walls. Obviously, a lava lake, remaining in a crater after an explosion, cannot be the source of magma. Therefore, the hypothesis of initiated volcanism was suggested (Ronka, 1968). /118

According to this hypothesis, the impact of a meteorite could cause a volcano in the place where the crater was formed, and could be the trigger for endogenous processes. In this case the agents causing the magma to rise are: a) the breccia and jointing zone below the floor of the crater formed; b) a reduction of pressure below the crater due to the removal of the rock mass which causes a lowering of the melting point and the formation of magma; c) the change of thermal conditions due to the faster cooling of rocks exposed in the crater. To this can be added the melting of rocks due to the shock waves. This hypothesis is very attractive; however, the extent to which it can be applied is still unclear.

Mainly it is not known how the heat transfer increases through the crater and, correspondingly, the faster cooling of the interior could cause volcanism. If the interior contains a magmatic focus or a heated plastic zone, material in this focus below the center of the impact crater should be cooled faster and should subside owing to its increased density. The hot material flowing from the periphery, in its turn, will cool and subside, etc., that is, a convective cell, if it also does not occur, will "engulf" the material at a depth rather than pinching into the crater.

A lowering of the melting point due to the removal of pressure is so small that it can be disregarded. According to a graph compiled by L. B. Ronka (1968, p. 178), the depth of a 90-km crater is approximately 3 km; this gives, in lunar conditions, a pressure reduction of 150 atm at a rock density of 3 g/cm^3 . Possibly the figure of 3 km is considerably understated; we suggest that the initial crater was 20 km deep. Then

the pressure below it fell by 1000 atm. But in order to reduce the melting point of basalt by 1°C , one must drop the pressure by approximately 80 atm (Belousov, 1966, p. 46) and below a crater 20 km in depth the melting point is only displaced by 12°C , and beneath a 3-km crater, by 2°C . This is clearly insufficient.

The energy of a shock wave does not guarantee fusion. The radius of the fusion zone during impact, according to calculations, is 0.035 of the radius of the zone of jointing (Bills et al., 1968, p. 16), and, according to drilling information on meteorite craters, is even less. The amount of energy for one unit of matter in a shock wave during propagation is inversely proportional to the area of the wave front (without allowing for losses through warming-up and rock deformation). Therefore, whereas the temperature in the melting zone increased by 1200° , in the center of the breccia lens, it increases by no more than 25° , and, on the boundary of the jointing zone, it increases by 1.5° . /119

Apparently, the main agent causing the appearance of initiated volcanism must be the breccia and jointing zones beneath the impact crater (Fig. 48). These zones either reach the existing magmatic foci or the magma penetrates them during a subsequent general lift of the magmatic front (possibly, after hundreds of millions of years). The first case is illustrated by the example of the Cardanus crater: its ejecta lie on dark mare rocks, but recent mare covers overlap part of the ejecta, that is the crater was formed while the mare was submerged and, at this moment, there was a huge magmatic focus, supplying the mare at a depth. The second version is that the numerous craters of ancient appearance are filled by relatively young mare matter. /120

Volcanic structures are well developed in impact craters with a diameter greater than 30-40 km (although they are sometimes seen in smaller craters, up to 15-20 km). But the depth of the zone of jointing is only known for craters with a diameter up to 1-2 km; for large craters, these depths are interpolated and, possibly, are overstated (Shteynberg, 1969). According to the graph by L. B. Ronka already mentioned, the depth of breccias for 30-40-km craters is 7-9 km; the depth of jointing is twice as great (Bills et al., 1968), that is, 14-18 km (Fig. 49). /121

If there are magmatic foci at these depths, it is valid to suppose that magma along the weakened zone emerges onto the surface. However, it would be just as valid to suppose that magma will force its way from such depths without a meteorite explosion, shall we say along the fault zone. Volcanic manifestations are seen in all craters over the lunar surface, and it must be recognized that there is the same universal development of magmatic foci or even a continuous molten layer. This is the inevitable result of volcanism not linked with meteorite impacts. Therefore, by accepting initiated volcanism, by the same token, we accept "natural" volcanism.

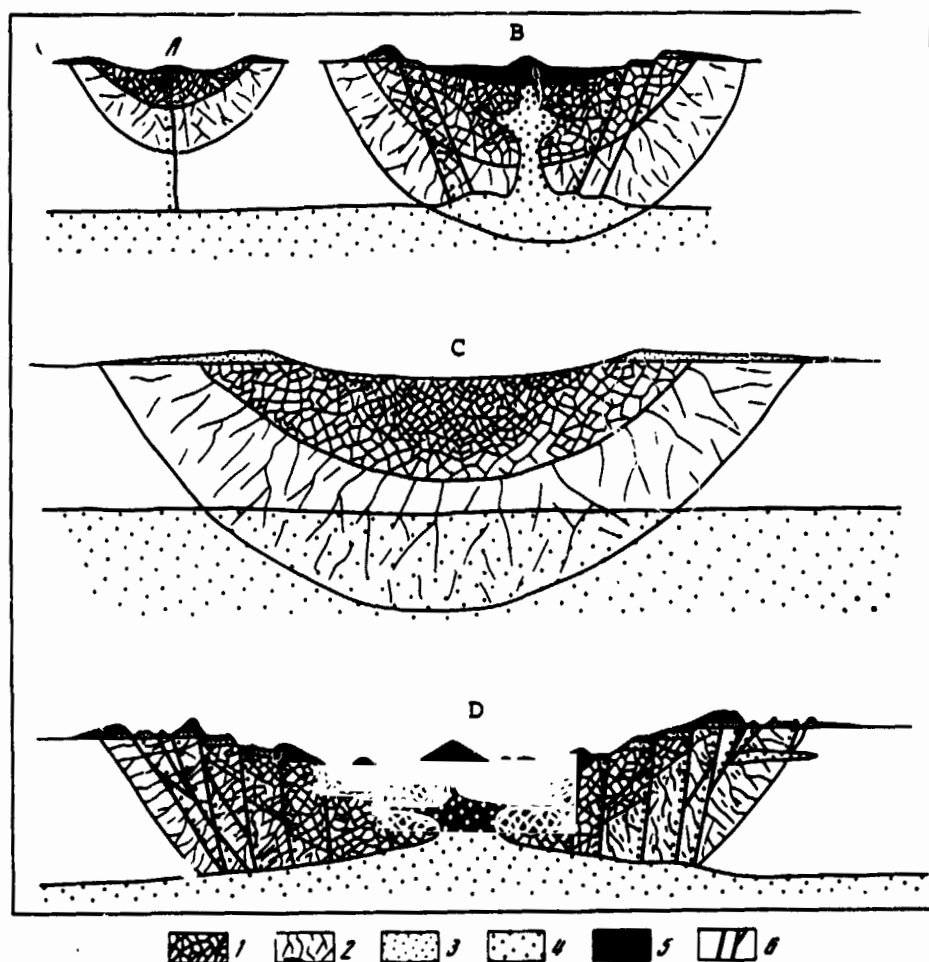


Fig. 48. A diagram of the development of initiated volcanism in impact craters: 1. breccias; 2. zones of jointing; 3. ejecta from impact crater; 4. magma-saturated zone; 5. effusives; 6. faults. A. A crater 20 km in diameter; the magma has only broken through in the center, there are no terraces. B. A 40-km crater: a fissure zone reaches the magma, the central part of the crater subsides, the magma flows through the crushed rocks to the bottom of the crater. C. A 50-km crater immediately after formation. D. The same crater, reworked by volcanism: the magma rises in a wide front in fractured rocks and flows to the floor and wall of the crater; the diameter of the crater is increased due to subsidences along the step faults.

In this way, craters greater than 30 km, to some extent or another, have been widened due to subsidence of the internal sections of walls. Evidence has already been shown of the steep fall and deep-lying nature of terrace-forming ring faults and

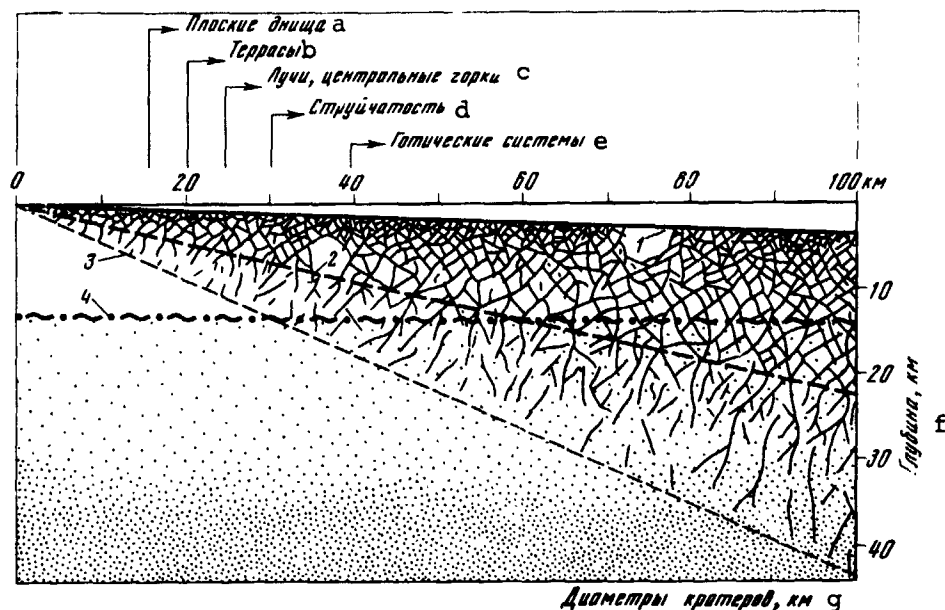


Fig. 49. The relationship between surface structures of impact craters and the depth of deformations below them: 1. depth of crater; 2. brecciation depth; 3. depth of jointing (1-3. according to L.B. Ronka, 1968); 4. suggested depth of magma-saturated zone.

Key: a. Flat floor
 b. Terraces
 c. Rays, central peaks
 d. Flow form
 e. Gothic systems
 f. Depth, km
 g. Diameters of craters, km

the links between them and volcanic manifestations. To this can be added the fact that the slide and slip of a layer of material from the wall to the floor of the crater (as was suggested by geologists of the American school) would result in the material being forced into the center of the crater and the central channel being blocked. In fact, as a rule, volcanoes occur in the centers of such craters.

Concentric fissures most probably behave in the same way as fissures above magmatic chambers near the surface on Earth, that is, they fall at steep angles to the center (conical) and from the center (ring) and are directly connected to the magmatic chamber (Yelisseyev, 1953; Markhinin, 1962; Sveshnikova, 1968; and /122

others). As a result, we obtain a structure of the caldera type, the indications of which are volcanic structures of the wall, normal in terrestrial calderas.

In this way, the impact of a meteorite should not only trigger volcanism, but volcanism of a completely specific type, causing the appearance of calderas and ring volcanic complexes. Therefore, the question arises: if the inside of the Moon, which is so prepared, responds to meteorite impacts by forming calderas, why do these calderas not appear without meteorites? In essence, this is not so important as is the reason for the localization of a caldera in a certain place -- the intersection of large faults or fissility, created by a meteorite impact.

Thus, if one accepts the wide development of initiated volcanism on the Moon, then by the same token, one must accept the following: a) the existence of magmas 10-20 km from the surface (during or after the formation of large impact craters); b) the "predisposition" of magmatic foci to form calderas.

It is also interesting to remember that near craters less than 25 km there is no flow form, the rays are small, the floor is cap-shaped, and the terraces and central peaks are poorly developed. A typical flow-ray picture is only seen near craters larger than 30 km, and they are fully expressed near craters greater than 40 km. This is probably linked with differences in the nature of impacts and explosions of meteorites of different size. But, probably, the deformations beneath the floors of craters with a diameter greater than 25-30 km reaches the magmatic activity zone, and fragmentation below 40-km craters considerably weakens the roof of magmatic foci, as a result of which the endogenous forces combine with those of the meteoritic explosion; the nature of the explosion itself and that of subsequent volcanism vary.

Terrestrial Analogs of Lunar Features

The morphology of terrestrial volcanogenic formations has now been studied in much detail. However, detailed examination of terrestrial volcanogenic forms according to data in the literature would go beyond the scope of this work and, furthermore, would be no more than a compilation. Therefore, several features of volcanic forms which have been directly observed by the author are given below

These examples are given since they are sufficiently typical for formations of this type. Each section is broken down into two parts: I. the form of terrestrial formations, II. a comparison of terrestrial volcanic forms and lunar ones.

Effusive and Pyroclastic Deposits

Part I

A field of young basalts in the Bazarcaj Pass (Armenia) consists of merging and overlapping flows 7-10 km in length with a width of a few kilometers, the depth of individual flows being from several meters to 40 m. Some flows emerge from the vents of cinder cones, breaching them on one side so that the remaining part of the cone assumes the shape of a crescent. Others underlie cinder cones, obviously emerging from the same channels, but often the effusion center is not marked by a cinder cone. The linear orientation of the group of cones indicates the fissured nature of the effusions. /123

By morphology, the flows of Bazarcaj are clearly divided into two types.

The first type is lavas of the aa type, with a coarse crust consisting entirely of large blocks of massive or cinder-like basalts. They are bounded by elevated walls and covered by subconcentric warp walls several meters wide; there are often fissures up to 5 m deep and 2-5 m wide in the furrows between the walls. Individual plates in the crust of flows are curved, twisted and placed vertically, so that they form obelisks 1-3 m in height. These flows are bound by steep external scarps.

The second type are pahoehoe lavas. They have a smoother surface, sometimes almost smooth or slightly undulating; there are no warp walls or marginal walls. These lavas are linked with drainage channels: trenches with slight elevated rims and a collapsed central section, as if a covered gallery had caved in. These are obviously typical of pahoehoe subsidence lavas of lava tubes. They are from hundreds of meters to several kilometers in lengths, tens of meters wide and 5-20 m deep. These and other lavas are in alternate layers in cross section and in places are hardly discernable. /124

It is characteristic that on a terrain with relatively steep slopes the flows run in long narrow tongues (Figs. 50 and 51), and lavas of the same composition spread out on a flat divide and have a smooth surface.

More ancient basalts in Armenia, Kamchatka and Sikhote Alin' do not retain their initial surface sculpture and merge into extensive even plateaus, the arrangement of which is linked with subsequent erosion. In cross sections it can be seen that the flows of this plateau are comparable in depth to those of Bazarcaj (5-20, up to 40 m), and are characterized by the same coarse surface crust (where it was preserved up to the moment of the following effusion). In this way, some ancient olivine basalts can form high, elongated "arms" with a coarse surface

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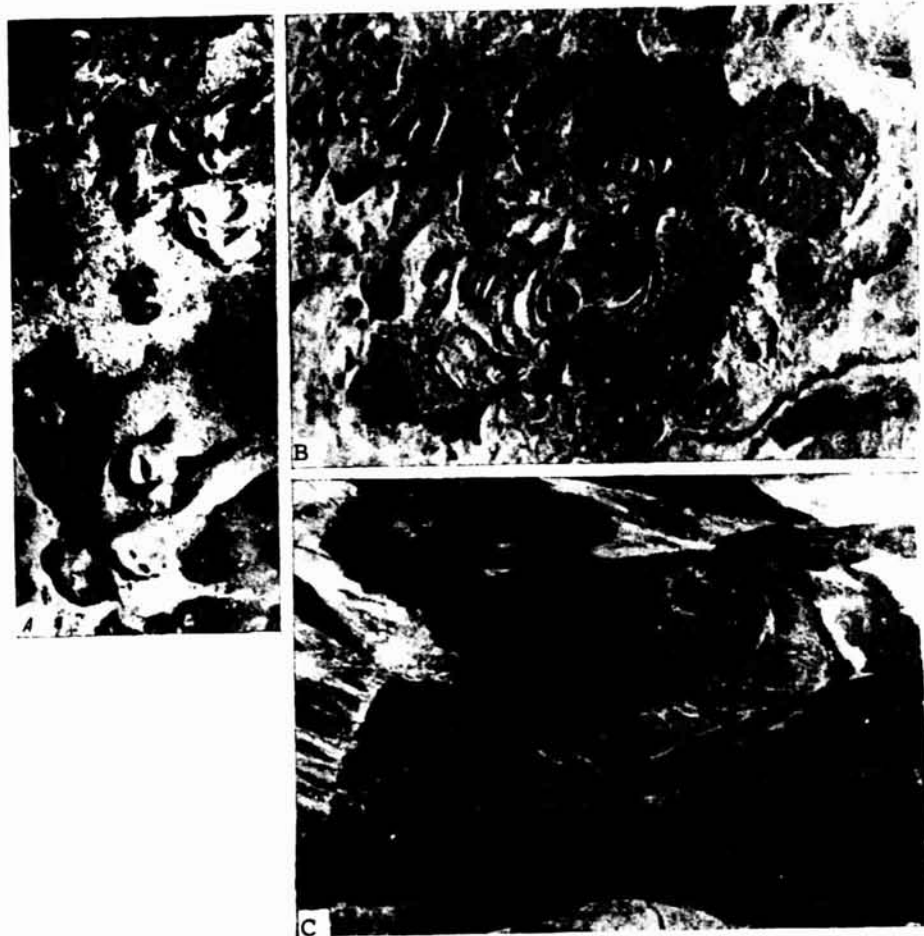


Fig. 50. Cinder cones and basalt flows on Earth, according to A. Ye. Svyatlovskiy: A. cinder cones on the slope of Tolbachik⁴; B. a basalt field in the Maymli River valley (frame width approximately 6 km); C. a flow 5 km long on the slopes of the volcano Novyy Bakenin, with side walls and warp walls.

in the same way as less basic basalts of Bazarcaj; and some andesitic basalts are spread in fine, quite even covers. Apparently, the morphology of the flows in the composition of andesites and basalts is determined not so much by the small differences in composition as the slope of the terrain, the entry rate of magmas and the gas-saturated nature.

⁴ [Translator's note: Place names are transliterated from the Russian when they cannot be found in a gazetteer.]



Fig. 51. Lava flows: A. a basalt flow 10 km in length in the region of the volcano Dzenurskiy; B. dacite flows and extrusions of the volcano Dikiy Greben'; C. An andesite flow in the upper reaches of the Kokhtan River (A-C -- according to A. Ye. Svyatlovskiy); D. a diagram of the dacite field of the volcano Bogultu (Armenia); 1. lavas; 2. the core of Bogultu; 3. effusion fissures; 4. transverse walls; 5. flow direction.

As a whole, the accumulation of a series of subsequent flows in one region causes the leveling of all irregularities of the relief, and basalts 100-200 m thick form a practically horizontal plateau (the region west of Severnaya Gavan', Sikhote Alin');

irregularities of the surface of individual flows are smoothed when pyroclastics fall on them and when soil is formed.

As opposed to basalt covers, fresh flows of andesitic dacites, dacites and rhyolitic dacites have greater depths, smaller areas and a coarse surface.

Rhyolitic dacite flows at the foot of the Ichinskiy volcano (the Kamchatka peninsula) extend for 1-3 km with a width of 1-2 km and a depth of up to 200 m. They begin from small dacite extrusions and are a direct prolongation of them, so that the boundary of the flow and the extrusion is scarcely discernible. During the flow the lava surface is crumpled into wide walls, with a horizontal range of 30-100 m and a vertical one of 20-30 m, and is scattered with massive obelisks up to 5-10 m high. The flows terminate in deep marginal walls and steep scarps.

The andesitic dacites at the foot of the Mount Aragats (Armenia) originate from fissures on which there are sometimes small volcanic cones. The surface of the flows at the eastern foot of Aragats is covered by numerous closed and half-closed sinkholes, tens of meters in diameter, divided by knolls and ranges. Here, the erosion network is even less developed, and this relief most probably reflects the initial sculpture of flows or has been formed by subsequent subsidences in the body of the flow (drainage or suffosion). The dacite plateau northwest of the Bogultu volcano (southwest of Mount Aragats) is situated on a gently sloping base and consists of several flows, the total depth of which exceeds 100 m. Whereas basalts from neighboring Aragats spread over the slopes and, as it were, "lick" the unevenness of the relief, filling depressions, the more viscous dacites of Bogultu form a "cap" superimposed on the underlying relief. Their area is approximately 180 km². In plan, the field of dacites has the shape of a trapezoid (22-24 km by 7-10 km) with long subparallel sides. This whole lava mass not only flowed from the volcano Bogultu, situated on the summit of the trapezoid, but from several fissures approximately parallel to the sides of the plateau. These fissures are marked by small walls, where there are visible manifestations of hydro-thermal activity and brecciation. The lava surface is relatively even; on it one can just discern traces of warp walls.

/125

/126

Rhyolitic flows, for example near the volcano Malyy Arteni, are not, strictly speaking, flows -- they are short enlargements of the central acidic extrusive body. Incidentally, the author has not seen a sufficient number of fresh flows of rhyolitic composition.

Ignimbrites are widely developed in Armenia. There are at least three interbeddings of these rocks in the effusive massif of Mount Aragats. Beginning on the slopes of Aragats,

they spread over a distance of more than 100 km. Their sources are not known; according to geographic information, one can assume that there are magma-producing fissures on the slopes. The depth of ignimbrites is small: from several centimeters to 10-20 m in paleorelief depressions. Wherever they are exposed in the erosive network or in quarries, it is apparent that ignimbrites envelop the underlying relief, filling its depressions, and, in this way, the relief is leveled. When rolling down the slopes of Aragats, the ignimbritic material is even detained in small basins, for example, on the north slope the crater of a small basalt cinder cone is filled with ignimbrites. Sometimes a thin layer of ignimbrites "flows over" small elevations, only scarcely reducing its thickness, which is impossible for lavas. Its chemical composition corresponds to rhyolitic dacites. There are no signs of erosion of the terrain when ignimbrites are superimposed; the latter do not even trap debris from noncemented lapillic cones overlapped by them (the Saralandzha region). The primary surface of ignimbritic masses, judging everything is very even, without any accumulations of material. There are no marginal scarps; the layers gradually taper away.

The deposits of directed explosions are represented in Kamchatka in the volcanic regions of Bezmyanny, Shiveluch and Kamen' (Gorshkov, 1962; Yemakov, 1969b). They stretch for approximately 10 km with a maximum width of 5-8 km; the depth varies from 100 to 200 m in frontal sections to 20-50 m in the main body of the flow, increasing in the depressions of a buried relief. The cover material consists of unsorted debris of rocks of exploded volcanoes and pieces of pumice; the size of debris is from sand and lapilli to blocks with a volume of several tens of cubic meters. The whole forms a completely noncemented mass, easily scoured even by seasonal streams, not only from the surface, but by suffosion. Therefore, the surface of the most ancient cover in the region of the Kamen' volcano has been completely altered by erosion, and on the cover of Bezmyanny only reworked portions of the initial relief are preserved: these are random accumulations of steep knolls and sinkholes resembling badlands.

The initial relief is seen best on aerial photographs of the Shiveluch cover. Here there is an interesting system of furrows and narrow walls. Some of them are distributed subconcentrically, perpendicular to the direction of the cover movement, similar to warp walls on lava flows. Other are elongated along the cover, sometimes curving and becoming concentric crests; the impression is created that tongues of material moved at different speeds, and the structure of individual tongues is similar to the flow structure of viscous fluids. The length of the furrows reaches 2-3 km, the width is from several meters to several tens of meters. Apart from these, the surface is covered with small, gently sloping knolls and basins; in the central part of the cover, 5-10 km from the main crater, there are several tens of

pyramidal accumulations, which are, according to G. S. Gorshkov and Yu. M. Dubik (1969), remnants of melted stone and ice blocks, which were ejected here from the main crater. The volume of these accumulations are a few tens of cubic meters. It is interesting that these blocks were either not formed from secondary impact craters or these craters were not formed, but were destroyed when the cover moved after the fallout. The rims of the cover of the directed explosion are steep and sharp, its depth increases towards the frontal section, the front cuts into the forest on the slopes with several tongues. All this indicates the movement of material after it fell to the ground. The wrinkled and furrowed deposit surface of the directed explosion is covered by pumice accumulations of pyroclastic flows with an even surface, shallow depth and with a characteristic diagram in plan, similar to frost patterns on glass.

Part II

To begin with, dark maria on the Moon correspond to basalts. One can identify individual flows by differences in their brightness, by the dissimilar density of small craterlets, and by extreme scarps visible on some photographs (Ranger 8 and 9, 1966; Wilshire, 1966; Whitaker, 1965). The depth of these flows apparently varies from several meters to 20-40 m. The large areas of these flows, the level surface, the flowing of lavas into narrow "bays" of the mare edge all indicate basalt composition. In any case, on Earth all lavas with a more acidic composition have a coarse relief. Judging by the wide distribution of dimple craters and drainage channels on maria, mare lavas correspond to the pahoehoe type. However, it is possible that there are also flows of aa: their vertical relief is less than the depth of the regolith and could have been completely leveled by the latter. In this case, some blocks, emerging from the regolith, could be remains of "obelisks" seen in aa lavas.

Here the similarity with present-day basalts ends. Normally, mare lavas have no marginal scarps; they do not form ridges at contacts with protrusions of the base; streams which have been interpreted occupy large areas. All this confirms the information on the extremely low viscosity of lunar basalts (Murase, McBirney, 1970). The presence of dimple craters several hundreds of meters in diameter indicates the wide development of deep pahoehoe mare lavas, whereas on Earth there is only a small amount of them. There are quite contradictory opinions on the question of the origin of rilles. After Ranger flights the opinion was put forward that rilles are collapsed drainage channels in lava (Ranger 8 and 9, 1966). However, drainage channels on Earth do not exceed several kilometers in length and, if this phenomenon exists on the Moon, it is on a much larger scale. This could be linked with the depths of lunar lavas, their viscosity or

congealing conditions. But, possibly, rilles are not drainage channels (see the section "Petal-like Craters").

The relief of dacite flows is similar to that of flows on the external slope of Tycho and some flows which run from the walls to the floors of large cirques. This relief is also seen on the floors of large craters. This, of course, should not be considered as evidence of the dacitic composition of corresponding lunar lavas, but the viscosity of these lunar flows is apparently similar to the viscosity of dacites. Otherwise, it is difficult to explain warp ridges, marginal scarps and ridges, and the great depth of lava flows when they are relatively small.

/128

Ignimbrites with their leveled surface and wide distribution would have been a similar analogy for rocks filling mare basins, if direct analysis had not shown the lava, basalt-like composition of mare material. However, there is still a possibility of discovering ignimbrites on smooth areas of the light highlands (among Altaic deposits). Possibly, the lightness of these areas indicates a more acidic material composition, but their level nature shows that the material was very mobile when deposits were made, which is characteristic of acidic ignimbrites, but not of all acidic lavas. It is interesting that in postmare craters the lava floors are lighter than the surrounding mare, that is, their lightness is not the result of the ancient nature of the surface. It is possible that some ray aureoles were formed by ignimbrites, but as yet this is only a supposition. Finally, it must be noted that rocks of basalt composition similar to ignimbrites are seen (Oleynikov, Starosel'tsev, 1968; and others); the increased degassification of lavas which poured out under lunar conditions could cause the wider development of such rocks on the Moon.

Deposits, very similar to those of the directional explosion of Shiveluch, are visible on the west wall of Tsiolkovsky (Gorshkov et al., 1970). The flow and ray relief around large craters is also very similar to the deposit relief of directed explosions; in those cases when such a relief is linked with the endogenous crater (Azarchel), it cannot be explained by meteoritic ejection. The fact that deposits of directed explosions are noncemented and easily eroded must quickly cause the disappearance of the initial relief, as on Earth; therefore, it is more difficult to identify them on the Moon.

Mare Orientale is a special case, where subconcentric ranges and furrows, very similar in diagram to the Shiveluch deposits, radiate from it in a wide belt. However, with all their similarities, the cover of Mare Orientale is 100 times greater than those of Shiveluch and Bezymyanny, the ranges and furrows are much longer, and the altitude gradients are greater than on terrestrial covers. Although there undoubtedly are volcanic

formations and tectonic disturbances in the belt around Mare Orientale, as a whole it is difficult to avoid the conclusion that this gigantic cover was formed during a monstrous explosion, obviously when an asteroid impacted.

Cinder Cones and Pit Craters

Part I

Most cinder cones are similar to each other, only differing in size. They consist of basalt cinders and cinder-like lavas with a bomb mixture, and partly welded and noncemented cones on the periphery. In plan they are rounded or slightly elongated, and the ratio of the major axis to the short axis rarely exceeds 2:1. The diameters of the bases are generally from several hundreds of meters to 1-2 km. Smaller cones tend to have the shape of a crater with an embankment, not that of a cone; there is an increased amount of lavas in the composition of the larger ones. With diameters of 0.2-2.0 km, the relationship of the cone height and the diameter of the base has an approximate form $H = 0.17D$; this curve flattens out somewhat for large diameters. Summit craters have diameters on the order of several tens of meters, but are only preserved in the newest cones. Sometimes young cones are seen in the craters of more ancient cones. The diameter of volcanic bombs is normally not more than a few tens of centimeters. Lava domes, formed during several effusions, are wider and lower than cinder cones, and merge with the surrounding flows. /129

Individual cones can be distributed in chains of 5-10-15 cones in a chain, the length of which can be 3-7 km (Anau, Kamchatka); the cone clusters form elongated zones several kilometers in length, for example, the central series of cones of the Gegam highland. When they are closer together, the cones form lava-cinder ranges from hundreds of meters to several kilometers in length. Obviously, these groups mark fissures, which are conduits. The composition of cones and their lavas is from basalt to andesite.

In some cases, the eruption center is not marked by a cinder cone, but a conical depression. At Bazarcaj there is such a conical depression with a diameter of 70-100 m and a depth of 20-30 m; streams of pahoehoe lava emerge from it, but there are hardly any cinders around it.

The main mass of cones is linked with areal effusions of basalts, but they are also frequently seen on the slopes of large volcanoes, when they appear during lateral eruptions.

Although the density of cinder cones can reach 5-6 over 1 km² for small areas, as a whole their density in plateau basalt

areas is much lower. In one area of the Sredinnyy ridge in Kamchatka (Uskichan-Anaun-M. Ketepana) approximately 300 well preserved cinder cones are distributed over an area of approximately 1100 km². Some of them have been destroyed by erosion; therefore, the total density could be estimated as 0.3 per 1 km². In the region of the Kl'ucevskij valley, according to A. N. Sirin (1968), their density is approximately 0.13 over 1 km². At Bazarcaj, approximately 20 cones have been identified on an area covered by recent flows, which gives a density of approximately 0.4 over 1 km²; but if one takes a large region with Quaternary lavas and cone remnants, the density is reduced to 0.1 over 1 km².

Part II

Terrestrial cinder cones and lava domes are very similar to knolls covering the floors of lunar cirques. The diameters of these lunar knolls, basically, are close to those of cinder cones (0.1-1.0 km in Aristarchus; 0.5-2.5 km in Tycho); on an average, the height is somewhat less, but is also in the range of several tens to several hundreds of meters. The density of these knolls in Tycho is 0.2-0.3 over 1 km², and in Aristarchus is 0.5-1.5 over 1 km², which agrees with the density of cones on plateau basalt. The area around lunar knolls is often softened, as if powdered with some incoherent material, probably ash. The knolls overlap fissures and more ancient flows and, in terrestrial cones, younger flows emerge from some of them. There are craterlets on their summits and occasionally ring scarps (traces of sommas?). Sometimes the knolls are joined into chains. In this way, the floors of some craters on the Moon with their knolls and flows are very similar to fields of terrestrial plateau basalts with their cinder cones.

Terrestrial and lunar cinder cones differ in the size of their craters: most terrestrial craters have diameters from several hundreds of meters to several tens of meters, whereas lunar summit craters (with almost similar base dimensions of the cones themselves) often reach a size of 300-500 to 1000-1500 m; and one can select a series of such forms with a gradual shift from a large cone with a small craterlet on the summit to a large craterlet with small walls and sometimes without walls, with only a dark aureole. /130

Furthermore, accumulations of cones are only found on the floors of some craters and on individual ancient mare (Altaic) areas. Basically, cones are not so much linked with regions of areal effusions on the Moon as are small craterlets on the order of hundreds of meters in diameter. Their volcanic nature is recognized by their dark aureoles, the grouping of craterlets in chains, the link with fissures, the increased depth, etc.

Obviously, some factors lead one to assume that, on the Moon, large craterlets with relatively small cinder walls are produced more often than cinder cones with small craters.

Stratovolcanoes

Part I

Examples of two volcanoes can be shown here which are better known by the author than others: Aragats in Armenia and Ichinskiy in Kamchatka. In general, their structure is typical of complex stratovolcanoes, and some features of their structure are useful when comparing stratovolcanoes with lunar forms.

Aragats is approximately 2 km high (above the level of the surface of the surrounding depression, filled with effusive and rubble rocks) and its diameter at the base is 40-50 km.⁵ Its base is formed by a basalt shield volcano with a diameter not less than 50 km and a height of approximately 1 km. In the core there is possibly an arch elevation of the base with a range of several hundreds of meters. There is a steeper andesitic volcano on the basalt shield, the rocks of which have evolved from andesitic basalts to rhyolitic dacites. In this way, the sequence of more acidic lavas has been completed several times by the eruption of small volumes of ignimbrite (in total several tens of cubic kilometers), after which the cycle is renewed with more basic lavas (partial recurrence). After the last eruption of ignimbrites, a large explosive caldera appeared on the summit (2-4 km), on the slopes there are flows of olivine basalt, and at the foot there are deep flows of dacites.

Olivine basalts, just as more acidic flows, have emerged from several tens of centers on the slopes of the massif, marked by cinder cones. Besides the conduits of these centers in the massif, the author has detected several andesitic sills, but they are not deep and quickly taper away; there are few movements along fissures since the whole massif is quite monolithic. On the other hand, dacites surrounding the foot of the massif are linked with long (up to 10-14 km) fissures, subconcentric to the massif, and there are signs of subsidence of the internal flank of these fissures. The whole massif of Aragats, together with the small volcanoes surrounding it, lies in an extensive depression, isolated in the northeast from basic rocks (Cretaceous-Paleogene) by large faults. /131

⁵ The author completely agrees with the point of view that Aragats is a Neogenic-Quaternary volcano (Amaryan, 1963; and others) and is not a dislocated mass of Paleogene effusives (Paffengold, Ter-Mesropyan, 1964).

The evolution of Aragats was generally standard, with the exception of ignimbrites. Normally there are either no ignimbrites in the products of volcanoes or there are so many of them that a large collapsed caldera is formed. On Aragats, several sub-concentric fissures have been formed and, possibly, the central part has settled somewhat. Obviously, this massif should be examined as a transition from normal stratovolcanoes to ignimbritic calderas. It is also interesting that ignimbrites appeared, obviously as the result of the gradual evolution of the magmatic focus, and their eruptions over time are close to those of basalts.

There is a group of smaller volcanoes around Aragats. One of them, Golgat, is a wide, flat basalt shield with indistinct boundaries, 8-12 km in diameter and 300-500 m high, and of elongated form; possibly, several centers flowed together here. Another basalt volcano, Arailer, with a base diameter of 8 km, is twice as high as Golgat, and is a regular cone, composed of lavas and breccias of andesites and andesitic basalts. The example of these two volcanoes indicates that with almost identical lava composition the shape of the volcanic formation is noticeably different.

The Ichinskiy volcano rises 2 km above the surrounding area, its diameter is 15-20, and its slope profile is slight concave. The upper part of the volcano is cut by a somma with a diameter of 4-5 km, in which there is a young cone which almost fills it (and the slopes of this cone and the atrio are overlapped by a glacier). In radial fissures in the central part of the slope and near the lower boundary of the glacier, one can see that the volcano consists of basalts and andesites with occasional inter-beddings of pyroclastics; there are remnants of cinder cones in this mass.

A string of rhyolitic-dacitic extrusions with flows branching from them extends over the slopes of the lower third of the basic cone at approximately the same height; this allows one to assume that here there is a magma-supplying fissure. (Ring faults can also be traced around the volcano, but this will be dealt with later in the section "Large Calderas and Ring Complexes.")

The Ichinskiy volcano can be considered as a representative of an andesitic basalt stratovolcano with a somma, but the ring chain of extrusions is not characteristic of volcanoes of this type, and, possibly, it is linked with the position of the volcano in a caldera.

Now on Earth there are tens of thousands of volcanoes and paleovolcanoes; of these more than 500 have been active in historical time (Tirrel', 1934; Ritman, 1964; Luchitskiy, 1971). Their morphology is determined by many factors, and volcanoes of one and the same composition can have a different form. But

generally a shield form is characteristic of volcanoes with a basalt composition, andesitic formations are represented mainly as regular cones, and composite stratovolcanoes with evolution from basic rocks to acidic ones have a tendency to form cones with a concave slope profile. The height of terrestrial volcanoes reaches 4 km above the base, and subterranean ones to 9 km above the sea floor. The volcanoes are normally fed along central channels, but when the volume of the volcano exceeds a certain critical limit, a large number of cinder cones and flows of peripheral ejections appear on its slopes. The material from these peripheral ejections forms a substantial part in the volume of large volcanoes; hence, a certain elongation in a northwest direction of the contour of Fuji is obviously caused by the accumulation of centers of peripheral effusions on the northwest and southeast slopes (Tsuya, 1968). The sizes of summit craters are within ranges of hundreds of meters; sometimes on the slopes there are sommas up to several kilometers in diameter; in some cases, lateral explosions of large blocks burst in the body of the volcanoes, forming asymmetrical craters. /132

In the décollements of paleovolcanoes, one can see that the diameter of conduits varies from hundreds of meters to 1-2 km, and intrusions, filling the surface chambers, are relatively small. Besides this, in these décollements, there are often ring, conical, radial and layered dikes. A. Ritman suggests that they can compose up to 20% of the volcano's volume. However, judging by the morphology of present-day volcanoes, the significant displacements are in no way connected with faults filled by dikes. Apparently, the compensating warping of the base, linked with the growth of the volcanic formation, envelops an area greater than the base of the volcano itself. Hence, there are gently sloping warpings at the base of some Japanese and Indonesian volcanoes; those in Hawaii warp together with a zone up to 400 km in diameter; many Pacific Ocean volcanoes are found in depressions bordered by compensating pinched walls (Menard, 1966). V. A. Yermakov (1969a) writes of the compensating nature of the Khapitsa basin (east of the Kl'ucevskij group) and, apparently, the whole Tolbachik-Kamchatka-Khapitsa river valley around the Kl'ucevskij group is to some extent a compensating sagging. Probably, the depression around the Aragats massif also occurred when compensating warping took place.

As yet little study has been done into the depth of burial of magmatic reservoirs below volcanoes, although there is information for some volcanoes on the presence of magmatic chambers in the first few kilometers below the surface (Shteynberg, 1964; and others), or even in the body of the volcano. As a whole, volcanoes are fed from great depths (20-30, 60, 70 km), and these chambers near the surface are only small intermediate foci.

Part II

On the Moon, the central peaks of large volcanoes have the greatest similarity to terrestrial volcanoes. As opposed to small knolls (cinder cones), the peaks of large craters are of complex composition. Often they are broken down into groups of individual or partly merging knolls. The latter can be elongated, with asymmetrical slopes, a flat summit or with large craters on the summit, or on the slopes opening on one side. One can sometimes see mantles of such material spreading from these peaks on large-scale photographs. On one of the central elevations of Copernicus, there is a dike (or a steeply falling stratum?), and on the other there is a somma with a new cone in it; obviously, these peaks were formed over a long time. External crater volcanoes also have a similar structure, for example, Piton peak, with its conical shape, complex summit crater and poorly defined radial crest (dike?). There are domes similar to the shield volcano Golgat and cones similar to Arailer. Large craters on such volcanoes, open on one side, can be compared with the craters of Bezmyanny and Shiveluch. Some suggested volcanoes on the Moon (Alps) have been classified mainly by their morphological similarity to terrestrial cones. /133

The difference between terrestrial and lunar volcanoes is more interesting. The height of lunar volcanoes with similar base diameters, on an average, is less than those on Earth, and the base diameters are considerably small. Even in large cirques, the diameter of the central peak does not normally exceed 15-30 km, and the largest peaks are formed from several smaller cones flowing together. Lunar volcanoes have domed or gently sloping cone profiles; apparently, on the Moon, there are no volcanoes with a concave profile which are characteristic on Earth. On the Moon there are often elongated volcanoes and volcanic crests, whereas on Earth these are seldom seen and normally break down into several merging cones. There are few cinder cones on the slopes of lunar volcanoes. Probably, this is linked with the small size of lunar volcanoes; on Earth there are masses of cinder cones near volcanoes of sizes which are not seen on the Moon: Aragats is 40-50 km over the base; Kl'ucevskaya Sopka is 60-70 km, Fuji is 40-50 km. One has the impression that large calderas have taken the place of large volcanoes on the Moon. Finally, the number of volcanoes on the Moon, even small ones, is reckoned in hundreds, whereas on Earth it is in thousands and even tens of thousands, although the land surface on Earth is only four times greater than the surface of the Moon.

Large Calderas and Ring Complexes

Part I

On Earth there are now from several tens to several hundreds of calderas, ring and central complexes (this uncertainty is due



Fig. 52. The caldera Aso (diameter 20 km), according to H. Williams. A. A relief model of the caldera; the festoon outlines and central massif are visible. B. A diagram showing the extent of ignimbritic covers (shown in black around the caldera) -- they extend over distances of up to 80 km from the caldera.

Key: a. Aso

due to the different interpretations of the volume of these terms), since all ancient structures are included. In formation they are quite different (Figs. 52 and 53).

There are some classifications of terrestrial calderas (Williams, 1941; McCall, 1963; Svyatlovskiy, 1967; Elston, 1969; McBirney, Williams, 1969; and others). However, they are too fractional for the purpose of this work, since we still cannot subdivide volcanic craters with the same detail on the Moon. For example, in a detailed classification by H. Williams (McBirney, Williams, 1969) basalt craters are divided into the Masai type -- a block subsidence on an area greater than the base of the volcano; the Hawaii type -- subsidence on the summit of a shield volcano due to summit and rift effusions, and the Galapagos type -- subsidence due to drainage into the sills and lateral effusions. On the Moon, we cannot distinguish what caused subsidence and what the parameters of the initial shield volcano are, since these three types can be joined into one. The Katmai type of calderas classified by these authors can hardly be distinguished on the Moon from the Krakatoa type.

Some classifications, for

example, W. E. Elston (1969) to a considerable extent rely upon the chemism of rocks forming the caldera structure; hardly anything is known of the chemism of rocks of volcanic lunar craters.

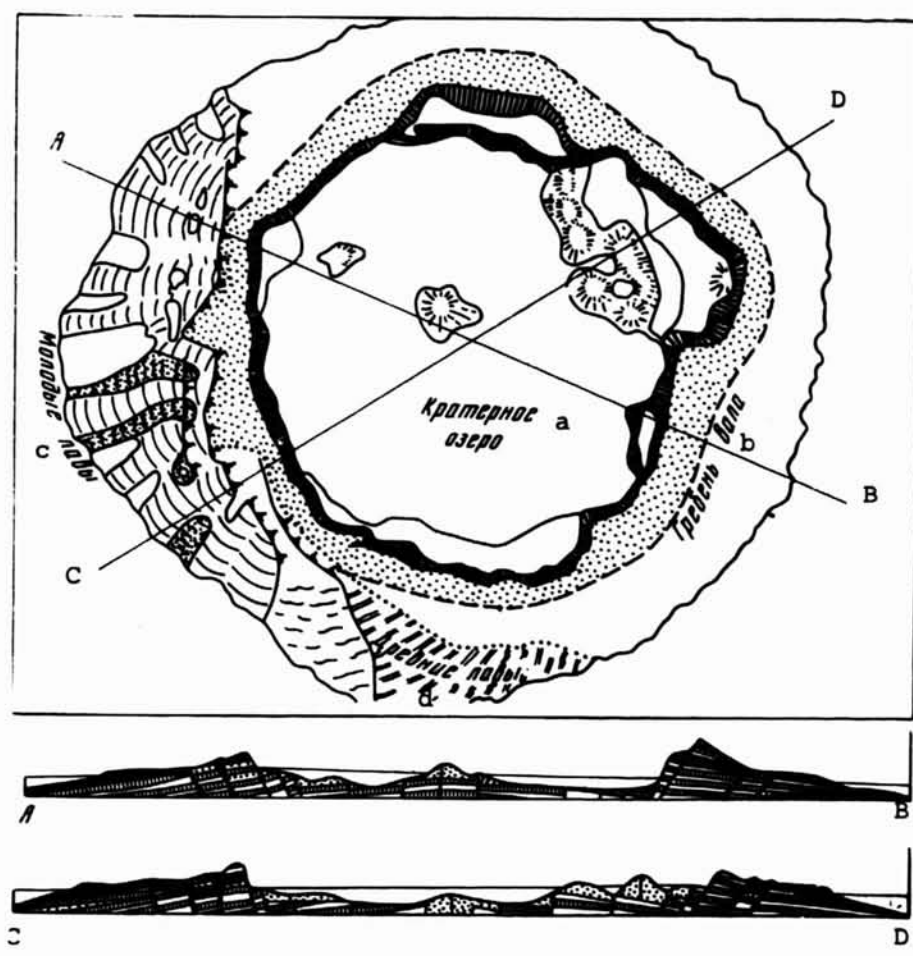


Fig. 53. The caldera Niuafu'ou (diameter 4.5 km over the crest of the wall). Fissures along which effusions passed are shown by thick jagged lines.

Key: a. Crater lake
b. Crest of the wall
c. Young lavas
d. Ancient lavas

Therefore, in this work it is sufficient to divide calderas into three groups: Hawaiian type, Krakatoa type and large volcanic and tectonic depressions (predominantly ignimbritic). This division is closest to the classification by R. L. Smith (1965), but this author limits the last group to resurgent ignimbritic calderas.

Hawaiian type calderas. They are found on summit shield basalt volcanoes and volcanic plateaus; their volume, in comparison with those of volcanoes is comparatively small. The size of these calderas ranges from 2-5 to 15-20 km (Williams, 1941;

/135

Aprodov, 1965; Macdonald, 1965; McCall, 1965, 1969; Erlikh, 1969). Their external slopes, that is, the slopes of volcanoes, are formed by liquid lava, giving an even surface, and the boundary of the volcano with the base is hardly discernible morphologically. Caldera-forming faults fall vertically or steeply inside, and in plan have a ring or festoon shape. In some cases, there are several ring faults, embedded one on the other; Batur is a 7-km caldera in a basin, measuring 10 x 14 km; Niuafo'ou is a 5-km caldera, with internal terraced slopes; Newberry measures 8 x 6.5 km, with a series of concentric fissures and cinder cones chains at the foot of the volcano. Normally, the volcanoes are quite similar in composition, and, after subsidence, there is little change in the type of effusions and magmatic products, but sometimes dacites are found in the caldera or pumice is ejected. The dimensions of subsidences are from hundreds of meters to 1 km.

Subsidences are linked with a weakening of magma pressure over time when there is recession of a magmatic column or when there is lateral drainage of it (Williams, 1941), or the result of peripheral effusions (Macdonald, 1965; Jonson, 1966; Menard, 1966). G. U. Menard believes that, in underwater volcanism, the pressure of the water cover, as it were, compresses the body of the forming volcano, overlaps the lateral fissures and prevents lateral effusion; therefore, effusions only pass along the central channel, forming a conical structure. The magma only begins to drain along the lateral channels when the summit of the volcano rises above the level of the sea, and then a caldera is formed in the summit part of the volcano.

/136

Apparently, some calderas can be shown as transient varieties between Hawaiian and other types; this is possibly an evolution from one type to another. Thus, in the caldera of Zavaritskiy two external subsidence rings (with diameters of 10 and 8 km) are cut into the basalt-andesite structure with a small amount of pyroclastics, which increased as the volcano evolved; the formation of a third internal somma (3 km) is linked with ignimbritic ejections (Gorshkov, 1967).

Krakatoa type calderas. They are seen during catastrophic explosions with the effusion of large volumes of pumice and pyroclastics. The crater is partly formed when the upper part of the crater is removed and partly due to the devastation of the magmatic chamber near the surface and the collapse of the cover. The calderas have dimensions of several kilometers: Krakatoa -- 7-8 km, Tambora -- 11, Crater Lake -- 7, Tao Rusyr -- 7.5, L'vinaya Past' -- 7 x 9 km.

Andesites and basalts are the most typical rocks of exploded cones. There are mainly olivine basalts in the volcanic structure of the caldera Tao Rusyr, and bipyroxene andesites among

postcaldera pyroclastic flows; the caldera L'vinaya Past' is cut into the stratovolcano of basic composition, and explosion pumices consist of dacites (Gorshkov, 1967); the exploded part of the caldera Krakatoa consisted of andesites, and the marginal cone Rakata of olivine basalts.

Normally, in calderas which have formed, the extrusive domes grow or new volcanoes form. Some calderas are formed by purely explosive means, without collapse; they are relatively small (Shiveluch -- 2 km, Khangar -- 1.5 km; Bezmyanny -- 1.5 km).

During the main paroxysm, an explosion lifts a huge mass of fragmented material and pumice into the air (1.2 km^3 -- Bandai, 2 km^3 -- Bezmyanny, 18 km^3 -- Krakatoa). In some cases, the main part of this material falls directly onto the external slopes of the caldera, reaching a depth of tens of meters (60 m of pumice for Krakatoa); the fresh relief of these deposits is similar to badlands. During directed explosions, a pyroclastic mass is hurled across relief elevations and falls at a distance from the crater in the form of a tongue stretching for many kilometers; after this fallout, the mass is shifted by inertia over the Earth, and a ridged and furrowed diagram appears on its surface. Small explosions usually follow the main explosion, and the main mass of the ejection is overlapped by pyroclastic flows which smooth its relief.

The boundary between explosive calderas of the Krakatoa type and ignimbritic depressions is somewhat indeterminate. Thus, the depression of Crater Lake, in the state of Oregon, with a diameter of 10 km, is on the base of Mazuma, a destroyed stratovolcano surrounded by deposits of explosive pumices, and indicates that there was collapse of this depression after the explosion (Williams, 1941). Besides pumice around the depression, there are fields of ignimbrites. Apparently, the boundary between these two types can be shown by the presence or absence of an initial accumulative cone, which is not typical of ignimbritic depressions. /137

Volcanic and tectonic depressions, ignimbritic and basaltic calderas and ring complexes. These are the largest volcanic basins on Earth and attracted most attention when searching for analogs of large lunar volcanoes (Fig. 54).

The size of these depressions reaches several tens of kilometers: Mogollon -- 120 km; Island Park -- 30 x 35 km, Rotorua -- 16-20 km, Moka -- 50-65 km, Vellis -- 20-25 km, Taymber -- 35 km, Toba -- 35 x 110 km, Monastyrskaya -- 16-20 km, Zholmanskaya -- 14 km, the Severnyy Pribalkhash'ye depressions -- 15-35 km, the Chatkala-Kuraminsk region -- 15-25 km and many others (Kopteva, 1964, 1970; Healy, 1964; Fedorov, 1965; Hamilton, 1965; Elston, 1965, 1969; Arapov, 1966; Ignat'yev et al., 1968; Smith, Bailey, 1968; Sheridan et al., 1969; and others). Magmatic

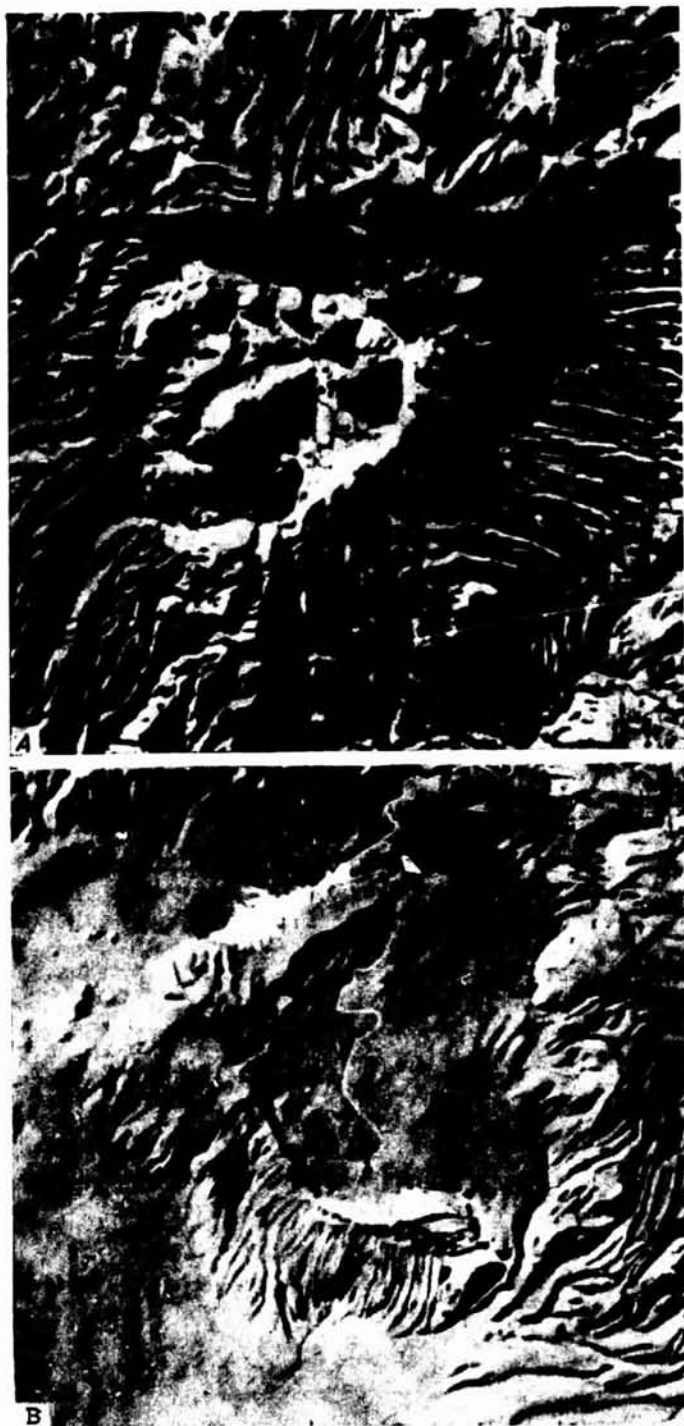


Fig. 54. Relief models of calderas. A. Vellis (20 x 25 km); B. Island Park (30 x 35 km).

ring complexes (Fig. 55) have the same order of dimensions: the South Australian rings -- up to 160 km, the Popigaj structure -- 90 km, the ring intrusions in Nigeria -- up to 30-40 km, Mull (Scotland) -- 10 x 15 km, Ossipee (New Hampshire) -- 13 km and others (Yeliseyev, 1953; Avdeyev, 1965; Reynolds, 1956; Turner, 1963; Crawford, 1963; Sveshnikova, 1968; and others). Large amounts of eruptive material, mainly ignimbrites, are linked with these depressions. According to R. L. Smith (1963), fields of pyroclastics with a volume of 70-80 to 4000-30,000 km³ can be attributed to volcanic and tectonic depressions and, other types -- from 2-10 to 400-1000 km³ -- to calderas.

In structure, ignimbritic depressions can be compared with large lunar craters. They are found on large, gently sloping anticlines, or on the even surface of the base, and not on an accumulative formation, as calderas of the Hawaiian or Krakatoa type. The massive ejection of pyroclastics in ignimbritic calderas directly precedes subsidence, is synchronized with it or even occurs after subsidence (Erlikh, 1966, 1969; Smith, Bailey,

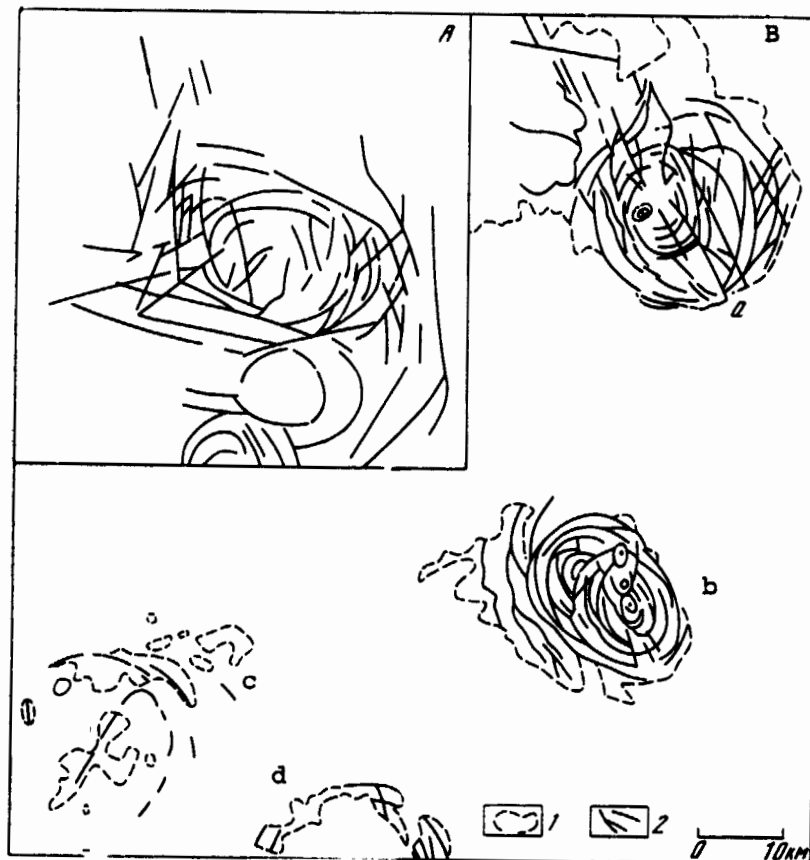


Fig. 55. The concentric formation of intrusions. The interpretation diagrams have been compiled according to photographs taken by Gemini artificial satellites: A. a fissure system in the batholith of the California peninsula; B. concentric plutons of the Sahara: a. Jebel Yuvenat; b. Jebel Arkenu; c, d. badly exposed intrusions; 1. outcrops of bedrock; 2. fissures, ranges and furrows. These intrusions are similar in structure to concentric craters on the moon.

1968; Byers et al., 1969; Bailey, 1969). Volcanic activity occurs along fissures on the floor of the depression and along its rims, which, at a depth, are confined to ring and conical dikes; extrusion chains and volcanic vents are often localized on the rim of the depression. The deep cuts of paleocalderas show a complex picture of subsided cylindrical blocks, alternating with lens of sills, concentric intrusions, ring, conical and radial dikes. The surface structure of subsidence, caused by effusions, is normally badly eroded or completely cut, but it is often possible to determine the size and direction of vertical displacements: normally these are subsidences with a

range of several hundreds of meters to 4.5 km (Sveshnikova, 1968). Volcanoes and extrusions are found in the center of the depression, which, at a depth, correspond to the intrusive bodies of the stock type.

The development of depressions is a long one, although the moment of the basic subsidence is often well determined (Byers et al., 1969). There are festoon depressions, consisting of several merging downwarps, as, for example, Aso. Sometimes, there is a migration of the center of magmatic activity (Mull, Ardnamerchen), as a result of which chains of ring complexes may occur: for example, the Saraféré complex (Nigeria) consists of five concentric zones with contiguous rims, with diameters from 5.5 to 13 km (Turner, 1963).

In areas where straight elongated faults divide the base into blocks, these depressions take on an irregular shape, with rectilinear boundaries (Kopteva, 1970).

/139

Sometimes there are "underdeveloped" depressions: open rings of extrusions without subsidence (Erlikh, Trukhin, 1969).

Normally, the radial structures in these depressions are not expressed on the surface, but are only shown by dikes at deeper décollements; apparently, there are no significant displacements along these radiating cracks with the bulging-up of a dome. The floor of the caldera again begins to bulge up in so-called resurgent (regenerated) depressions after the main collapse.

Most researchers explain the occurrence of ignimbritic depressions and ring complexes by the fact that at a shallow depth beneath them were large magmatic foci, and after massive effusions from these, the cover of the foci lost its support and subsided along the ring fissures; volcanism was later localized along these fissures and in the center of the depression. The depth of foci beneath present-day calderas is thought to be 1-6 km (Zubin et al., 1969), and in paleocalderas is 2-10 km; for small calderas, up to 10 km in diameter, the focus is often indicated at a depth of 1-3 km (Sveshnikova, 1968). But, on the other hand, there are intrusions which have solidified several kilometers from the surface, and there are no caldera subsidences above them. Apparently, apart from the shallow depth, the area of the focus should be taken into account, as should its dynamic conditions and tectonic situation. Thus, T. V. Perkalina (1966) believes that subsidences appear during the recession of the magmatic front above "weakened" magmatic columns, and is linked with a certain stage of development of the region.

/140

Since similar ring depressions are very important for understanding lunar processes, some examples of these structures should be shown.

W. Hamilton (1965) described a very interesting caldera, Island Park, west of the Yellowstone Park plateau. Its dimensions are approximately 30-40 km, it is of Pleistocene age, and it is well preserved. The caldera is noticeably polygonal. It was deposited on a gently sloping shield volcano, formed (at least in the upper sections) by acidic ignimbrites. The remaining rims of this shield are only 3-15 km in width, and the gentle external slope and steep (35°) internal scarp are sometimes terraced. W. Hamilton believes that subsidence took place almost simultaneously with the formation of the shield; the subsided block was overlapped by the same rhyolitic ignimbrites which effused from many fissures. After collapse, the ignimbrites were gradually replaced by tholeiite basalts. The basalts belong mainly to the pahoe-hoe type, as do lunar lavas, and drainage channels, similar to lunar rilles, are seen on them. Rhyolite extrusions were ejected along the rims of the caldera during latter stages, and its eastern part was overlapped by deep rhyolitic covers. The author's conclusion that the rhyolites were formed due to the liquated separation of basalts which peeled off into the upper part of the magmatic focus is a very interesting one. This mechanism is feasible when interpreting many lunar craters. It is true that there is no complete analogy, since the depth of the Island Park caldera, on an average, is only 200-300 m (although of course the size of subsidence is much greater).

The Vellis caldera in New Mexico (Smith, Bailey, 1968) has measurements of 20 x 25 km and a depth of 0.6 km (the height of the crest above the present-day floor). A huge dome rises in the center, and, between it and the caldera rims, is an open ring of rhyolite extrusions. The caldera is filled with rhyolites and their pyroclasts, and the wall consists mainly of precaldra rocks. R. L. Smith and R. A. Bailey give the following history for the formation of the Vellis caldera: 1) the appearance of an extensive anticline and ring fissures above the magmatic chamber; 2) effusion of several hundred cubic kilometers of ignimbrite; 3) collapse along the ring fissures, when the central blocks subsided more than the peripheral ones, so that terraced sides occur; the second and third stages were practically simultaneous; 4) filling of the basin by acidic vulcanites and sedimentary rocks; 5) the elevation of the central anticline and radial cracking; 6) extrusions and effusions of rhyolites along the ring fissures inside the caldera; 7) the attenuation of volcanism, and solfataras. R. L. Smith and R. A. Bailey showed that similar features -- the bulging-up of domes in the center, rhyolite accumulations along the sides -- are also inherent in other ignimbritic calderas: Krid, Taymber, Toba and others.

/141

W. E. Elston (1965, 1969) described the 130-km Mogollan plateau as a Miocene subsidence structure, framed by ring fissures. The depression is filled with rhyolites and basalts and bounded by

ring of rhyolite and basalt cones, extrusions, dikes and flows. In the center is an andesitic cone with a 5-km caldera and three more calderas with diameters up to 15 km around the rims. The volume of ejected material is more than 10,000 km³.

Paleozoic depressions of the Severnyy Pribalkhash'ye, studied by V. V. Kopteva (1970) and I. G. Shcherba (1970), are volcanic and tectonic depressions with dimensions from 15-20 to 40-50 km, filled with effusives which flowed out during the prolonged subsidence of the basins. The rims of the depressions (often polygonal and irregular in shape) are marked by ring flexures, faults, dikes, volcanic centers, intrusions, and, in the center, there are often magmatic bodies or, as in the Chubaraygyrskiy basin, internal calderas. The wide development of these structures, as I. G. Shcherba remarks, causes the honeycombed, looped structure of the region, so that the elevations are narrow steptoes between the numerous volcanic and tectonic basins, under each of which is a magmatic focus. The condensation of magmatic bodies along the caldera rims should have been expressed when they were formed by the accumulative volcanic relief and, apparently, by some elevations; the same applies to the central blocks.

Similar structures at Tien Shan were described by V. A. Arapov (1966); here the diameters of the troughs are 15-25 km.

The Ichinskiy depression in Kamchatka is similar to ignimbritic calderas, but products of which it is composed differ. Ichinskiy, a somma-volcano composed of andesite and basalt, rises in the center of the depression. The internal (first) ring structure is shown by a chain of dacite extrusions fringing the volcano on the lower third of the slope.

There are also ring faults near the very foot of the basic cone, forming a second ring; the side facing the volcano has subsided (several hundreds of meters). In the upper reaches of the Goldavit' River (northeast sector) an obsidian dike approximately 1.5 km in length and up to 50 m deep is injected along one of these faults; its gradient is not known, but, judging by the relief, it is almost vertical. A second dike, which is radial, enters the body of the basic cone and, possibly, joins the first.

There is a third ring structure 16-18 km from the main summit. It is marked by two chains of obsidian extrusions, subconcentric to the volcano. Some of them are scarcely exposed and are interpreted as fields of hydrothermal variations (in fact, these are not extrusions, but intrusions). Possibly there are also tectonic movements here (the Payalpan crest). Almost on the same ring in the southwest is a basalt cone, Cherpuk, with a large flow.

Finally, the fourth ring is traced in the east in the form of a scarp 500-700 m high. This scarp is at a distance of 25-30 km from the center of the volcano, and is formed by a half-ring fault, along which the internal part has subsided with the volcano, forming a caldera subsidence. Precaldera Neogenic formations, smoothing the crests of the scarp, are only exposed inside the caldera at the very top levels and only in the deepest breaches near its rims; therefore, the amount of subsidence can be estimated as 500-700 m, possibly up to 1000 m. The boundary of the caldera cannot be traced in the west; here there are only northwest and weaker northeast faults. The floor of the whole basin is overlapped by Quaternary basalts and andesites no less than 200-400 m deep, with individual flat lava volcanoes, and also incoherent Quaternary deposits. /14?

The whole depression is a fairly typical ring structures: a ring fault, two concentric fissures zones with acidic dikes and extrusions, a central volcano with a large somma. However, it is not formed from pyroclastics, but lavas, and, moreover, not of acidic, but basic and intermediate composition.

Part II

Petal-like craters on the Moon probably correspond to Hawaiian calderas. They have smooth, gentle external slopes which merge imperceptibly with the surrounding terrain, a steep, sharp internal slopes; they have no subsidence terraces of the normal appearance or complicating structures such as ring dikes. The size of petal-like craters are comparable with those of Hawaiian calderas (10-30 km). The absence of rays indicates a weak explosive nature, that is, they are primarily lava formations. Whereas neighboring craters often show the link with the tectonics of the area, petal-like craters are similar to each other, and their disposition and their shape are not controlled by fractures of the base; therefore, apparently, they are directly linked simply to a volcanic structure and its roots.

On Earth, the development of a shield volcano does not necessarily cause the appearance of a caldera: instead of this, on the shield there can be a small crater or strato-volcano of a more acidic composition. Therefore, it is natural to expect that on the Moon some of these volcanoes will also be without calderas or will be crowned with steep-sloped cones. Apparently, domes on the mare surface are also shield volcanoes without calderas.

Petal-like craters differ from Hawaiian calderas by their great depth and insignificant nature of volcanic structure in comparison with the caldera itself. Furthermore, domes without calderas are normally smaller than those with petal-like craters.

Some large craterlets on the Moon with diameters up to 10-20 km or even large craters, for example, the 35-km crater between Mare Autumni and the crater Schlüter are similar to calderas of the Krakatoa type (explosions with collapse). Morphologically, mature craters, Bessel, Briggs and others, are closer to this type, but they are much larger than terrestrial calderas of this type, considerably deeper and surrounded by lower, but wider volcanic formations, and are also terraced.

On the Moon many craterlets with diameters of a few kilometers are similar to explosive craters without collapse; however, these craters are not surrounded by remnants of a large volcanic formation, but only by comparatively small walls; furthermore, on Earth only small explosive craters are joined into chains.

Volcanic and tectonic depressions, ignimbritic and basaltic calderas and ring complexes are more similar to large lunar craters than any other terrestrial forms, including the problematic astroblemes. Apparently, concentric craters, complex cirques of the Alphonsus type, graben-craters of the Bosovich P type and mutually intersecting structures of the Main-Challis type belong to this type of depression. Primitive rings correspond to ring dikes on Earth. This could also be the possible origin of some stream-form craters. Volcanic accumulations on the walls and in the center of cirques, the gradual subsidence of the internal sections, the filling of the floor by effusives and pyroclastics, concentric structures, the merging of some cirques into a single structure, and tectonic elevations of the walls are seen in all these structures. /143

But the differences between lunar cirques and terrestrial calderas are very apparent. Lunar cirques are much deeper, have much deeper walls and concentric structures (in terrestrial calderas they are normally interrupted); the central cones in lunar craters do not rise above the level of the wall crest, and they are small in comparison with calderas (only some peaks in lunar cirque approach the size of, for example, the Ichinskiy volcano). The number of these structures on the Moon is comparable with that of ring complexes on Earth but, on an average, they are much larger than terrestrial calderas and are much more numerous than small volcanoes, a considerable number of which are only complicating structures with respect to large cirques.

Thus, lunar flows and covers are morphologically very similar to terrestrial ones, only differing in the scale of some details. The same can be said of cinder cones, although on Earth there are many more of these than explosive craters (having similar diameters), and on the Moon, apparently, the picture is the reverse. There are many volcanic trenches, crests and craterlet chains on the Moon, and on Earth there are few. In individual cases, lunar volcanoes are similar to terrestrial ones;

on the whole, they differ noticeably from them in shape and size. Lunar volcanogenic craters and cirques differ considerably from terrestrial calderas and ring complexes both in structure and in size and distribution, although both of them have much in common.

As a whole, as opposed to the Earth where they are more central volcanoes than calderas, and the latter often only appear as the result of evolution of the former, on the Moon the reverse picture is seen: here, the formation of calderas and ring complexes occurred on a much larger scale than the formation of central volcanoes.

Extent of Volcanic Features on the Moon

After volcanic features had been mapped in those regions which had been photographed in sufficient detail, it was possible to approximately evaluate the number of volcanic features among the remaining features of the lunar surface. It must be stressed that these evaluations are only very approximate: they do not give accurate figures, but only an order of magnitude.

Calculations on the best-photographed regions (the southern half of the central part of the visible disk, the equatorial zone of the far side, part of the northern polar region and several smaller areas) showed the following. Reliably defined accumulative volcanic forms occupy 0.5% of the lunar surface, and, together with assumed ones, up to 1-3%; volcanogenic craters are from 3-5 (reliable) to 9-12% (with assumed) of the overall area; ancient mare regions of areal effusions are 15-20% (this includes the floor of submerged craters of unknown origin), mare formations, together with dark mare, occupy up to 30-35% of the lunar surface. Quantitatively, volcanogenic craters with a diameter greater than 20 km are comparable with craters of meteoritic or unknown origin; in some areas, they compose from 1/4 to 1/2 of all craters or even more, but this evaluation is even more subjective than the relatively large number of ancient forms which are either craters or simply ancient depressions filled with lava. /144

Of course, the relative number of volcanogenic forms varies from area to area, but remains constant for sufficiently large regions. Hence, for example, the calculations of areas shown above were made without allowing for Zond 8 material. Similar calculations using Zond 8 photographs for an area of 1.6 million km² gave the following figures: volcanogenic craters -- 4% (reliable) to 9% (with assumed ones), volcanoes -- 2-3%, regions of areal effusions -- 13-20%; in total, 19-32% of the area.

Obviously, some of the assumed forms, in fact, can be of nonvolcanic origin. But, on the other hand, mapping was carried out on features which were mainly well-preserved, and, apparently,

many ancient volcanic formations were not identified since they were distorted beyond recognition by subsequent processes. Whereas the number of volcanogenic forms among ancient formations is the same as among younger ones, the overall amount of accumulative forms on the Moon in any case makes up not less than 1% of the whole area, and volcanogenic craters make up not less than 6-10%.

By taking into account that primary-volcanogenic forms, craters reworked by volcanism, and regions of areal effusions are seen over practically the whole surface of the Moon, it must be assumed that the fusion of the inside of the Moon was very widespread during their formation and the magma probably issued onto the surface from a massive melt layer or a system of connecting magmatic foci through many channels; this magmatic zone ought to be at a relatively shallow depth; it is also natural to assume that, during this long process, all areas of the lunar surface underwent a volcanic reworking stage at one time or another.

While this work was being prepared for publication, the United States Geological Survey, together with NASA, issued a geological map of the near side of the Moon on a scale of 1:5,000,000, compiled by D. E. Wilhelms and J. F. McCauley (1971). It is a generalized junction of a geological map on a scale of 1:1,000,000, compiled by various authors within a general program using one method. The legend to the map gives morphological characteristics of different regions and objects, their relative age and genetic interpretation.

It is interesting to compare this map with ours. It shows highland plains which were formed by volcanic material deposited in a liquid state (that is, lavas or fluid systems). In general, these plains correspond to ancient maria on our map, but their area is smaller than ours, and the contours are shown in general form; many small areas of ancient maria are not marked. Some regions which we believed to be ancient maria are shown on the American map as mantles of ejecta from circular maria.

/145

At the same time, the use of originals of Orbiter photographs allowed American researchers to interpret many rugged areas of the highlands (which we left as white spots) as regions densely covered by volcanic formations, endogenous craterlets, etc. In this way, the general volume of volcanogenic formations on areas outside of craters is approximately the same on both maps.

There are fewer separate volcanoes on this map than on ours, but basically this is the result of simplifications and omissions when changing from a 1,000,000 to a 5,000,000 scale.

Volcanic craterlets measuring up to 10-15 km are shown in groups of chains and clusters and linked with structural lines;

here, the possibility that they are of secondary impact origin is not ruled out. Among larger forms (20-40 km), only craters having smooth external slopes which are relatively well-preserved are considered to be volcanogenic, and the internal structure, the interconnection between craters and their disposition are not examined. Therefore, the number of large volcanogenic craters on the American map is obviously understated.

Faults on this map are not shown completely, whereas the age differentiation is given in great detail: craters are broken down into eight age categories, highland formations into seven. Apparently, when this map was compiled, special attention was paid not to structures and their origin, but to stratigraphy.

The Age of Lunar Volcanism

The absolute age of lunar samples fluctuates from 3 to 4.5 billion years, and the age of dark mare lava is between 3.3-3.9 billion years. All dark mare formations, stratigraphically, are distributed almost identically; since relatively ancient and comparatively young sections of these maria were subjected to tests, no significant increase in this interval can be expected.

Intensive volcanism took place on highlands before these mare basins were filled. It is more difficult to determine the length of this. Calculations of crater density on ancient (light) mare of the highlands showed the following. If one accepts the crater density on dark maria as one unit, on highlands the crater density is 32 units (that is, 32 times greater than in the maria), and the age of light maria, filled by thalassoids, has quite different values -- from 5 to 30. (Incidentally, here it was found that the formation of the mare fill was isolated in time from the moment when the thalassoid itself formed.)

But only the relative age of ancient maria can be found in this way and only approximately: we know nothing at all on the intensity of crater-forming processes 4 billion years ago, nor their rate of attenuation over time; therefore, nothing can be said of the absolute length of highland volcanism using this material.

/146

Some analysis of the absolute age of lunar soil indicates, as it were, a much earlier beginning of differentiation processes -- some 100-200 million years after the accretion of the Moon -- but this requires confirmation.

Furthermore, it is not known if this volcanic process was continuous or broken down into stages, separated by some time interval, and, especially, whether mare volcanism was a direct continuation of the highland one or whether these were two independent phases. The author believes that the second suggestion is more probable.

First, there are small areas of ancient maria scattered over all the highlands, whereas dark maria in the main mass are concentrated on the near side, forming a gigantic merging field from Mare Fecunditatis to Oceanus Procellarum and from 30°S latitude to 60°N latitude.

Secondly, mascons are only linked with dark maria (although, of course, it is possible that they will be seen on the far side, whose gravitational field has been studied little). Both facts indicate some differences in the formation mechanism of dark and light maria.

Thirdly, measurement of gamma radiation by the Apollo 15 showed that the concentration of radioactive substances in highland rocks is considerably lower than in dark maria (Arnold et al., 1972). One has the impression that radioactive elements accumulated in highland rocks from a relatively small volume of matter, whereas processes which produced dark lavas enveloped much larger volumes. Therefore, the hypothesis that the highland crust occurred directly after the Moon was formed, when a certain amount of accretion energy had been spent on fusing part of the lunar shell, is worthy of attention. Afterwards, progressive fusion of the Moon's interior began, which was supplied by the heat of radioactive decay; it was completed by the effusion of dark lavas enriched with radioactive elements.

Apparently, the intensity of volcanism began to decline after dark maria were formed. But how long did this last? Is there still volcanism at present? If there is, how developed is it? When attempting to solve these problems, we come up against interesting contradictions.

On one hand, now the Moon ought to have a deep, hard shell.

One and one half billion years after the Moon was formed, a large quantity of melt and radioactive substances was brought to the surface; the heat, brought with the melt and generated by the radioactive substances, began to disperse into space. Having exhausted, to a considerable extent, its energy reserves, the Moon, in the next 3 billion years, gradually solidified so that now the thickness of the hard crust, according to calculations, is 300-500 km (Fricker et al., 1967; Mayeva, 1971; and others). Recently, seismometers placed on the Moon registered moonquakes to a depth of approximately 800 km; researchers processing the seismograms believe that the depth of the hard shell should be not less than this value (Latham et al., 1972). Finally, measurement of the Moon's electrical conductivity show that to a depth of 700-900 km the temperature of matter is insufficient for its fusion (Wetherill, 1971).

With such a shell, it is difficult to imagine how magma can now burst through to the upper horizons of the crust or even to the surface. Apparently, several hundred million years ago, the situation was somewhat different from today: the shell was much thinner, but still did not let magma through.

/147

However, on the other hand, volcanism took place on the Moon until quite recently, and, apparently, is still active. There are indications of repeated volcanic activity in such craters as Tycho and Aristarchus (Strom, Fielder, 1968, 1970), whose age, according to the number of small craters overlapping them, does not exceed 200-400 million years, and, possibly, one order less. Rays of one of the youngest craters, Copernicus, in places are overlapped by mantles of dark material, obviously volcanic. Some determined endogenous craters (for example, Wright and Shaler) are as well preserved as Tycho and Aristarchus. In Aristarchus and a number of other points, there is still endogenous activity (Kozyrev, 1963; Middlehurst, 1967; Chapman, 1967; Hartmann, Harris, 1968; and others).

It appears that information on the great depth of hard crust is contradicted by data on the relatively recent manifestations of volcanism. The aim of this work is not to answer that question. Only the following should be noted.

Calculations of the Moon's thermal history should not be considered final, since the initial radioactivity is not known exactly, nor is the temperature at the moment after accretion, nor the degree of convective nature of the Moon's interior, the role of zonal melting (and it is difficult to allow for the effect of partial fusion processes), magmatic differentiation and much more. The results of magnetometric measurement also allow for ambiguous interpretation (Ward, 1969; and others), and it is possible that the anomalous electrical conductivity at depths of 200-250 km is linked with the presence of residual magmatic foci found at the base of the relatively low-melting "crust" above the high-melting "mantle." This stratification of the Moon is suggested according to petrologic information (Smith et al., 1970; Danes, McNeely, 1971; and others). Finally, the seismometers not only registered moonquakes at a depth of 800 km but a swarm of subsequent tremors similar to those which are observed when magma moves toward the surface before an eruption. One must also remember that on Earth earthquakes are registered at depths of 400-700 km, and this does not interfere with the existence of a partial fusion zone at depths of 100-200 km, from which magma emerges to the surface.

In this way, it is possible that there are now residual magmatic foci in the Moon's hard shell. In order for these to exist, there must either be reserves of radioactive elements (that is, the shell is not differentiated completely) or a link between

the foci and the depth zones of magma generation. The latter assumes the lunar shell to be very permeable, which could be explained by the low pressures deep inside the Moon and the increased affluxes which "shake loose" the shell.

But, in any case, almost all volcanic structures on the Moon were formed, as we know it, by very ancient paleovolcanism on a gigantic scale, and present-day residual volcanism is no more than a weak shadow of those ancient events.

Peculiarities of Lunar Volcanism

/148

In the section "Terrestrial Analogs of Lunar Features," it was shown that relatively small volcanic formations (flows, covers, explosive craters and cinder cones) both on Earth and on the Moon, in general, were quite similar. At the same time, large volcanoes and calderas on Earth and on the Moon differed notably from each other both in structure and in size and distribution. Apparently, this can be explained in the general plan by the following.

The morphology of lava covers is determined by their composition, temperature, gas saturation and volume. The chemical and mineralogical composition of lunar lavas is not so different from that of terrestrial basalts; the temperature of these and other lavas during effusion (judging by the melt temperature of lunar samples) also differs little. The volumes of lunar flows are comparable with those of terrestrial flows of plateau basalts. The similarities of these factors also determines the similarity in the morphology of lava covers which form. Some differences are linked with the congealing conditions of lunar lavas in a vacuum and their smaller gas saturation, but, apparently, they are not so great as to significantly distort the observed features of similarity.

The similarity between lunar and terrestrial cinder cones and explosive craters, apparently, is also determined by the similarity of the mechanism causing their formation. Both of these form in places where volcanic channels emerge on the surface. When lava, rising along these channels, reaches an explosive level, a violent separation of the gas phase begins in it. This "boiling" of lava is expressed by effusions forming small accumulative or excavation forms. Here, differences can occur due to the smaller force of gravity, which increases the depth of the explosive level and the scatter of debris, but the basic mechanism probably remains the same.

But the difference in the structure and distribution of large volcanoes and calderas apparently depends more on overall planetary differences between the Moon and Earth, such as: the intensity and depth of magma formation, the nature of

differentiation, the degree of outgassing, the dynamic region of magmatic foci, the depth and structure of the crust, which, in the final analysis, is linked with the disparity between the masses of the Earth and the Moon, and, obviously, the rate of evolution of these planets. It would be very interesting to show the degree of influence of any of these factors on the morphology and degree of development of any of these structures, but now it is difficult to do this for even one of the factors shown above, to say nothing of many.

Here, many processes depend directly on several factors mutually affecting each other, and the change of even one of them brings with it consequences which are difficult to forecast. Little study has been made of the comparative value of all these factors and their consequences; one should not talk of quantitative evaluations. Progress in this direction leads to a better understanding of processes here on Earth, and, in the near future, when we have more detailed material on Mars and other planets, it will be possible to make far-reaching conclusions on the evolution of different types of planets.

Some reasons are examined below which could explain the specifics of lunar volcanism. It must be stressed once again that at the present time one is limited in these questions by more or less well-founded assumptions.

Dynamic Regime of Magmatic Foci

/149

The study of material on terrestrial calderas and ring complexes convinced the author that the most significant factor causing large subsidences is the massive emergence of magmatic material on the surface in a relatively short space of time; as a result, the magmatic pressure on the cover of the focus is sharply reduced, the cover cannot react plastically, and collapse takes place.

This massive, momentary emergence of magma suggests that the magmatic focus is not deep. If the volcano is supplied from depths on the order of several tens of kilometers, apparently there are a few channels linking the foci with the surface. When the central channel is already pierced, the surplus magmatic pressure will at first be released through it, the channel will be gradually developed, and additional channels will form -- everything becomes more difficult. These channels do not link with each other; otherwise, one could expect that lavas effused from neighboring volcanoes would be very uniform. In Kamchatka and in the Caucasus, there are examples where active volcanoes, at a distance of several kilometers from each other, erupted simultaneously: one was basic lavas, the other, intermediate and acidic. Apparently, at a depth of several kilometers, the pressures overlap all peripheral fissures, leaving one central

channel (Menard, 1966), which moreover can be "choked" and contracted with the formation of small unthreaded intermediate foci.

When these channels have a comparatively small cross sections (from hundreds of meters to 1.5 km, one judges by the diameters of deeply cut cores), their carrying capacity will be limited, the effusives will reach the volcano on the surface relatively slowly and the foci will be emptied slowly. The gradual growth of the body of the surface stratovolcano is compensated by the gradual influx of magma generated in the interior and, correspondingly, the gradual warping of the base of the volcano together with the adjoining terrain; this is the way in which gently sloping compensation basins are formed, sometimes with pinched walls along the rims (Menard, 1966; Moor, 1969).

If the magma approaches on a sufficiently wide front close to the surface, it can use the surface fissuring zones which remain relatively "open" due to low pressure, and can be effused at many points at once. Apparently, this occurs so quickly that the cover has no time to react plastically, and, instead of warping, collapse begins, with the appearance of new fissures, that is, new paths for the magma; the pressure rarely falls in the focus, and secondary boiling-up begins; effusion and collapse linked with it quickly develop. During these paroxysms, enormous amounts of ignimbrites of intermediate and acidic composition are effused, that is, large foci near the surface on Earth are predominantly intermediate and acidic. It has not yet been determined why this is so: due to the melting of the crust, assimilation or hybridism, or due to the prolonged differentiation of the basalt focus slowly bursting upwards. But in any case, if on Earth a melt, formed of a "basalt layer," begins to move towards the surface on a wide front, when it reaches the "granite" layer, it causes melting in this layer, since the melting point for a granite eutectic is much lower than the temperature of a basalt melt for those depths. A cap of acidic melt will occur above the basalt focus and will pierce the surface of the first. Possibly, this can be partly explained by the association of acidic ignimbrites with basalts, which effuse behind them. There are no ignimbrites in many ring structures, and there are many more basic rocks than acidic ones (the first intrusion center of Mull); there is also information on the wide development of ring magma-conducting channels in trap regions (Avdeyev, 1968).

/150

As is known, there is now no solid melt zone in the Earth's shell, but even above the partial melt zone of basalt from the mantle at waveguide depth, there are numerous conducting channels, sumps, magmatic chambers and peripheral foci.

On the Moon there is wide distribution of calderas, impact craters reworked by volcanism and countless regions of areal effusions, overlapping the whole surface in a dense mosaic. This

allows one to assume that during the Moon's history there was a period of intensive, widespread fusion of its interior. This conclusion agrees with information from lunar samples which have been analyzed: until now, all the samples investigated are rocks which have undergone differentiation, that is, the fusion stage.

During this fusion, the hard crust of the Moon should have been saturated by magmatic foci. Although the composition of these foci was predominantly basic (basalts, anorthosites), the effusion dynamics were apparently determined not by the composition, but by the position of foci and their proximity to the surface.

In this way, it is extremely probable that at some period on the Moon there were large foci of basic magma near the surface in great quantities. Massive, simultaneous effusions from them must have created not central volcanoes, but large volcanic collapse depressions. Furthermore, it is very probable that these foci connected with each other and with large magmatic reservoirs, supplying the mare basins; then, the exhaustion of the basic reservoir or one of the communicating foci should have caused a pressure drop in the other foci linked with them, which would make subsidences easier. Just as on Earth there are practically no accumulative forms composed of ignimbrites, so on the Moon there are no large basalt domes which have not undergone collapse -- effusions and collapses were close in time, if not synchronous. Apparently, there never were large domes; the bulging-up which began was immediately replaced by effusions and collapse.

This process must have been intensified by influxes, "loosening" the cover of foci, and the smaller force of gravity (less pressure in the crust, the "seal failure" of the cover, the formation of peripheral fissures and effusions along them, creating a deficit of magma below the center of the volcano with subsequent caldera collapse).

Schematically, the formation process of a large volcanogenic crater on the Moon can be shown in the following way. At a depth of 10-20 km a magmatic focus is formed, the diameter of which is commensurate with that of the future crater. Its cover gradually melts, shakes loose, and finally an effusion from many centers occurs over a wide area; the lavas which are very fluid spread widely. Collapse of the cover along ring fissures occurs as a result of the drop in pressure in the focus. After subsidence, volcanism is concentrated in the ring (most permeable) zone, building up the wall of the forming crater, and in the central part of the crater, that is, along the shortest route. It is probable that the most gas-saturated and acidic derivatives penetrate the surface in the center. Subsequent subsidences cover the whole block bounded by ring fissures, even if effusion

/151

takes place on its periphery⁶. The gradual widening of the caldera into a focus of new external rings cuts the internal part of the accumulative wall which is formed, and continuing effusions overlap the submerged blocks; in this way, an asymmetric, terraced wall with volcanoes in the center and on the wall is formed. After areal effusions, deeper magmatic reservoirs which supply the given focus near the surface are temporarily exhausted on adjoining maria; the drop in pressure causes new subsidences in the crater.

One must note that likening lunar basalt volcanism to terrestrial ignimbritic volcanism meets with certain difficulties. Some of the basic characteristics of caldera-forming ignimbritic volcanism are: a) an extremely rapid emission of very large volumes of effusions, which is obviously linked with the foaming of large volume of magma, and b) the great mobility of ignimbritic masses, which allows them to move great distance from effusion centers and, by the same token, not "encumber" the region of a forming caldera. On the Moon, apparently, the mobility of effusives is guaranteed by the low viscosity of lunar basalts, which is one order lower than terrestrial basalts; as a result, lunar basalts can move farther away from basalt centers more rapidly. But this reason can cause the rapid effusion of large volumes of basalts, which, on the Moon, can replaced the foaming of ignimbrites -- this is not fully understood.

Differentiation and Outgassing

The nature of differentiation of lunar magma is determined by too many unknowns to a priori forecast its results (Walter, 1965). For example, hardly anyone expected that on the Moon there would be such specific rocks as anorthosites. Thermal conditions, the size of foci and the degree of their convective nature, the degree of outgassing of magmas, the smaller force of gravity, apparently slowing down liquation but accelerating crystallization differentiation (Green, 1965), the absence of a sedimentary shell and much more have an effect on differentiation. In any case, lunar matter can produce even more surprises, and information on chemical analyses of mare lavas must not be extrapolated to highland regions and to formations such as explosive, volcanogenic craters or central volcanoes.

We still do not know why the viscosity of lunar lavas is one order less than that of terrestrial basalts (Weill et al.,

⁶ Thus, when the volcano Sakuradzim, on the edge of the caldera Ayr, erupted in 1914, the subsidence isolines did not correspond to the contours of the volcano, but of the whole caldera, with a maximum subsidence in its center (Williams, 1941).

1907; Murase, McBirney, 1970). If these lavas help to form a petal-like crater (corresponding in the first approximation to calderas of the Hawaiian type), this would explain some features of such a crater. The majority of lavas, which on Earth would create a large volcano of the Hawaiian type, on the Moon, due to low viscosity, would flow over extensive, shallow lava fields, merging with the surrounding mare rocks. Correspondingly, the height of the dome formed should be less, the area greater, and the boundaries more indistinct. Apparently, when distinguishing a dome on the lunar surface or outlining the boundaries of a petal-like crater wall, we are only outlining the distribution region of the most viscous portions of lava, and in fact the area of the volcano, crowned with a petal-like caldera, is much greater. Some domes without calderas, whose boundaries are only visible along part of the perimeter and for the remaining length merge with the mare surface, serve as confirmation of this.

/152

But, apart from basalt-like lavas, differentiation on the Moon also causes the appearance of acidic rocks. Study of some samples brought back by the crew of Apollo 11 showed that their mesostasis consists of two immiscible liquids, one of which is enriched with silica (71-76%) and K_2O (6.6%) and has a reduced CaO content (1.2-2.4%), and the other is similar in composition to basalt (Kushiro et al., 1970). Obviously, during liquation separation of these liquids from the basic basalt melt, the acidic residue of the dacite type should be separated. In fact, among samples from the landing site of Apollo 12 was found a fragment with a silica content of 61%, K_2O , 2% (10-30 times higher than the average content) and a reduced CaO content, 6.3%. When this sample was studied in detail, it was found to include breccia fragments of a more basic composition, and the composition of the basic mass was even more acidic: silica -- 73.5%, K_2O -- 6.9%, CaO -- 1.2%. This fragment is the result of differentiation which had progressed farther than for mare rocks (Drake et al., 1970). The authors of subsequent research believe that some indications point to the ignimbritic origin of the granite mass of this fragment. As has been said earlier, there is information on the possibility of such liquation separation of basalts in terrestrial conditions, with the separation of rhyolites and dacites in a ratio of 5:1 to basalts (Hamilton, 1965).

It must also be noted that, whereas there are considerable quantities of anorthosites in lunar highlands, as was suggested by fragments of them in mare regolith, when there is purely differential origin of these anorthosites there should also be a residual melt of syenites (Yeliseyev, 1953).

The fact that there are such rocks on the Moon agrees with the existence here of forms thought to be extrusions and central volcanoes, and allows one to assume that there is a relatively acidic composition of some flows with a rough relief (Tycho).

The third fact which must be taken into account when examining the peculiarities of lunar volcanism is the extremely low content of water and volatiles in lunar lava samples ("Summary ...", 1970; Friedeman et al., 1970). Apparently, as a whole, matter on the Moon underwent stronger outgassing than matter in the Earth's shell. On Earth, water and gases, are bonded to a considerable extent in precipitation, deep-heated zones once more, again take part in volcanism, magmatism and metamorphism, and help to form the continental crust saturated with volatiles. On the Moon, with its reduced force of gravity, gases arriving on the surface should be dispersed into space in a short time, geologically, leaving the further circulation of matter⁷. It is possible that, when the gas and liquid phase left, the Moon a considerable contraction of the whole /153 body of the Moon was caused, both in individual parts of it (a reduction in the volume of magmatic foci) and as a whole -- subsidences on its surface (Green, 1965).

But, on the other hand, the undoubted presence on the Moon of volcanogenic explosive craters indicates that, at least in some foci, there was a sufficient amount of volatiles to create these craters. In general, when speaking of explosive craters or extrusions, one can scarcely depend on the composition of mare basalt-like rocks: this is equivalent to saying that the composition of Siberian traps can be used for the effusion characteristics of the volcano Bezymyanny or its extrusive dome. Furthermore, it is quite possible that the outgassed nature of lunar lavas is linked with processes taking place when these lavas are effused in a vacuum when there is a reduced force of gravity; both these factors cause the increased separation of volatiles, and their loss can be up to 9.7% of the weight of the rock (Hatheway, 1970). Incidentally, the wild foaming of the tops of lava covers could bring about the formation of a thin layer of ash on their surface and a softening of their relief; processes of this type have been noted for two terrestrial basalts (Koptev-Dvornikov et al., 1967).

In this way, the outgassed nature of lunar lava samples does not indicate the complete outgassed nature of all matter on the Moon during the period of maximum volcanism. Together with the fact that there are acidic rocks on the Moon, the question of the presence of ignimbrites on the lunar surface arises. Many researchers believe that ignimbritic magma is the

⁷ It is possible that some gases which are produced during magmatic, volcanic and impact processes can be linked with surface regolith by means of adsorption, and are subsequently buried with the regolith under new covers of volcanic and impact and detrital material (Gutkin et al., 1968). However, the capability of the regolith of such saturation is limited; moreover, in present-day regolith, judging by its adhesion properties, there are very few adsorbed gases.

result of fusion of the acidic crust (Milanovskiy, Koronovskiy, 1963; Healy, 1964; and others). But there is information which shows that, at least in some cases, ignimbritic melts appear as the result of evolution of basaltic foci (Erlikh, 1969; Aramaki, 1969; Bailey, 1969; and others) and, consequently, can also occur on the Moon. However, at the present time it is only supposed that there are ignimbrites on the Moon according to some morphological information (Gorshkov et al., 1970; Green, 1965; Guest, Fielder, 1968; and others). If, in fact, they are there due to the reduced pressures and periodic pressure drops during influxes, the ignimbritic process ought to be more intense than on Earth, and sufficiently large effusion of ignimbrites, as a rule, cause caldera collapses.

Scattering of Pyroclastic Material

It must be repeated once again that volcanic explosions on the Moon undoubtedly took place; otherwise, it is impossible to explain the occurrence of many craterlet chains, craters with dark aureoles, summit craterlets of many volcanoes, directed ejecta of the Messier ray type or the cover on the northwest wall of Tsiolkovsky, etc. Therefore, the question is to evaluate the size of explosive craters and the nature of distribution of pyroclastic material around them.

The size of an explosive crater on Earth depends on the strength of the cover and the force of the explosion (the pressure in the explosive chamber at the moment of explosion). The pressure in the chamber during catastrophic explosions reaches 2-3 kbar. One should not expect a significant increase of the explosive force. First, there is a limit to the pressure of water vapor -- the main agent of an explosion -- even if one assumes that lunar magmas are completely saturated with this vapor; secondly, a saturation such as this is scarcely possible: in fact, on Earth a considerable amount of the water taking part in volcanic explosions is not juvenile but reaches the magmas due to assimilation of deep waters and water bonded in the sedimentary and granite crust; furthermore, many catastrophic explosions on Earth are, in essence, phreatic.

/154

The mass and weight of rocks in the case of directed explosives and a diatreme are subordinate in comparison with the strength of rocks, and this is the reason. During such explosions, ejected rocks do not fall on the rims of the explosive crater proper, but are hurled many kilometers from it, that is, the force of the explosion here is obviously excessive, and the depth of the explosion is less than the deduced depth for a chemical charge of corresponding power. If the cover was supported by the weight of rocks until the moment of explosion, a normal explosive crater with accumulative walls would be formed; obviously, the pressure in the explosive chamber is not restrained

by the weight of the rocks, which are easily hurled 10-20 km from the crater, but by the strength of the cover, which, on the Moon, hardly differs from the strength of terrestrial rocks. In this way, the size of craters formed during catastrophic explosions will be no greater on the Moon than on Earth, which is a few kilometers.

But the weight of rocks should significantly influence the size of normal explosive craters (with accumulative walls) and the distance which pyroclasts are scattered, for the following reasons.

1. Owing to the lighter weight of the magma column in the vent, nucleation begins deeper (that is, the explosion level is reduced) and is more intense, volatiles are separated in a fuller volume which increases the "explosive nature" of the magma; therefore, the initial ejection speed of interparoxysmal explosions will be greater (Green, 1963).

2. With equal initial speeds, fragments on the Moon fly six times farther due to the smaller free-fall acceleration

3. With especially great speeds, the flight distance of fragments is increased due to the curvature of the Moon (Green, 1965).

4. The flight of fragments is not restrained by the atmosphere; this fact has a greater value the smaller the fragments.

5. The widening of the gas cloud after the explosion on Earth is restrained by the atmosphere (Pokrovskiy, 1964); furthermore, this hot cloud quickly rises into the upper layers of the atmosphere; the vertical component of the speed of fragments increases accordingly. On the Moon, explosive gases will expand without breaking and give the fragments additional speed; this expansion will also give an additional horizontal component to the trajectories of fragments hurled vertically or at steep angles.

When cinder cones are formed on Earth, ejecta have a speed on the order of 100 m/sec (Piyp, 1956; Kirsanov, 1968; and others), which at an optimum angle of ejection of 45° gives a distance of approximately 0.8 km, and, allowing for the somewhat steep angles of ejection from the vent, gives half as much. These figures coincide well with the size of terrestrial cinder cones. On the Moon, since there is less free-fall acceleration, the flight distance of fragments is 4-6 km, and material from a terrestrial cinder cone would be distributed on the Moon over an area 100 times greater; in this case, on photographs we would see nothing except an explosive craterlet, surrounded by a wide, low ridge, as in fact was observed. Thus, instead of cinder cones

with small summit craters, on the Moon there are wide craterlets with small ridges.

Ejection speeds during paroxysmal explosions, which occur from time to time in large volcanoes, reach 300-600 m/sec, and they are either directed quite steeply or at a gentle slant (10-30°). The ejection range is from 4-7 to 12-20 km, that is, material is deposited, to a considerable extent, on the slopes and the foot of the volcano itself (for example, the volcano Severgin). If these explosions took place on the Moon, the ejection range should be from 30-60 to 130-250 km; consequently, the ejecta would go far beyond the cone. Let us assume arbitrarily that half of the material of the volcano Severgin was deposited during such explosions. If this material had not been hurled in a radius of 5 km (the radius of the present-day space of the volcano) but 30 km, the height of the cone would be half as much, and the area around would be covered by deposits only 10-20 m in depth; on the Moon this would appear as ray systems. If one remembers that interparoxysmal eruptions on the Moon ought to distribute material much more widely, then it becomes clear why lunar volcanoes are not as high as terrestrial volcanoes of the same diameter and why central volcanic peaks of lunar calderas are so small in comparison with the calderas themselves. It must also be noted that if the ejection occurs from the central peak of a large crater (diameter approximately 50 km), even with a gentle angle of inclination, this ejection will pass over the wall crest (2-3 km high above the floor) and fall on its external slope. For example, 2-m blocks were hurled 10 km to a height of 0.4 km from the caldera Kakuto (Aramaki, 1969); on the Moon, they would have traveled more than 80 km and reached a height of not less than 2.5 km. Therefore, the leveled relief of the external slopes in some craters can be explained by this pyroclastic "powder" from the center of this crater. The ejecta which do not cross the wall crest are overlapped by lava flows of the floor, just as ejecta on the external slope are partially overlapped by lava lakes.

/155

Structure of the Crust

Whereas the size of calderas is basically caused by the depth and the size of magmatic foci, the roundness of calderas and "regularity" of their shape apparently depends on the degree of lateral uniformity of the crust.

Young and old mare rocks predominate predominate in area among volcanogenic formations on the surface of the Moon. As was said above, mapped mare occupy 30-40% of the surface, but in fact there should be many more of them since many ancient mare regions have been reworked beyond recognition by subsequent processes, and cannot be interpreted. Judging by all information, young maria consist of monotonic basaltic lavas. Ancient mare of the highlands are

morphologically indistinguishable from young ones and are probably formed of those same lavas. In any case, they should be sufficiently uniform in area. Even if one assumes that ancient maria are composed, for example, of anorthosites, this does not change the overall picture: basalts and anorthosites belong to one group of magmatogenic rocks and react to stresses in a similar fashion. Furthermore, young and old maria are often capriciously intermixed: areas of dark maria are seen on highlands, and remnants of light maria appear on dark lavas.

There are too few volcanic craters and they are too evenly distributed to distort this uniformity, even if their rocks differ greatly from the rocks of maria, and meteorite craters only increase the uniformity by mixing matter and redistributing it over the area.

Obviously, the uniformity of surface rocks can be extrapolated /156 to a depth of at least several kilometers. It is possible that deep horizons of the crust are characterized by a great variability in lateral direction, but this is hardly probable: this variability would affect surface structures. In fact, on the surface there are some differences between highlands and dark maria, but the highland substratum can be traced along remnants of the relief below all maria of an irregular shape. Apparently, this highland substratum is seen at depths of 20-60 km below the "basaltic" layer and the equatorial part of Mare Nubium (Fig. 56). Judging by the presence here of mascons, one can assume that there is another structure of the crust or a reduction of its depth only for the central parts of the circular maria; but these regions are only bounded by isolated "windows" in an unbroken monotypic crust.

Thus, in spite of the incompleteness of our knowledge, we can accept with a large degree of reliability that the lunar crust, with regard to substance, is very uniform.

The second peculiarity of the lunar crust is its relatively uniform distribution of stresses and absence of all traces whatsoever of large horizontal displacements. The largest displacements on the Moon do not exceed 20 km, and there are few of them; there are no geosynclinal trenches on the Moon, and linear depressions and extended straight faults, in general, are linked with the isometric basins of maria and are secondary to them; if there are folded dislocations, they are very poorly developed; there are no structures where thrust faults could be suspected, that is, there are no signs of considerable horizontal stresses localized in narrow zones on the Moon.

Northwest and northeast fissurings, developed everywhere and manifested in gothic fault systems near craters, show the presence of some stress field common to the whole lunar surface. The basic compression in this field is oriented meridionally: /157

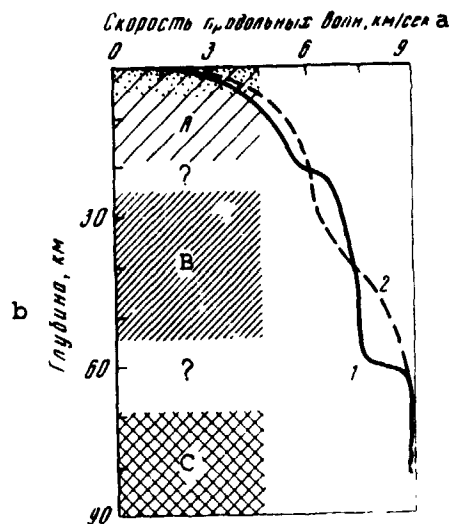


Fig. 56. The structure of the Moon's shell. The diagram is compiled according to information from seismic experiments carried out during flights by the Apollo 12-Apollo 15 spacecraft (Latham et al., 1972). 1. A model of the velocity profile with discontinuous accelerations; 2. a model with gradual increase of velocities (insufficient information does not make it possible for a choice to be made). A. A layer with velocities up to 6 km/sec (basalt?); in the upper part of the layer there is a scattering zone, apparently consisting of fragmented and fissured rocks; B. a layer with velocities up to 7.5 km/sec (anorthosite?); possibly this is not a separate layer but a transition zone between horizons A and C; C. a mantle, velocities up to 9 km/sec (hyperbasites?).

Key: a. Velocity of longitudinal waves, km/sec;
b. Depth, km

northwestern and northeastern disturbances have the nature of cleavage face fissures, and meridional ones, of detachment fissures (Elston et al., 1971; Fielder, 1963). But these disturbances do not have an independent significance: there are no large horizontal or vertical displacements along them; they do not divide blocks of a different structure; finally, they appear as secondary, additional structures, complicating ring faults. These fissure systems are poorly developed as they move away from ring faults.

The structure of the Earth's crust is much more complex. There are continental, oceanic and transient types of crust; there are geosynclines and orogens, platforms and medial and oceanic crests, and many smaller types of structures. Deep fractures, active over tens of millions of years, divide blocks with different formations and crust depth. Here, if there is displacement on the boundary of two dissimilar blocks, the contrast of matter and structure along this boundary increases and, obviously, later the discharge of stresses will occur here, by the same token, again increasing the contrast and so on. (If, for example, a fault separates identical basaltic blocks and subsequently is "healed" by the same basaltic magma -- as apparently occurs on the Moon -- the crust will remain practically uniform).

All this points to the fact that on Earth magmatic and

volcanic activity occurs under a more rigid tectonic control than on the Moon. The position of magmatic bodies and effusive channels depends, if not completely, to a considerable extent, on the structure of the block "frame" and on the position of fractures, especially if movements along these fractures continue during periods of magmatism; relatively "pure" volcanogenic structures, including large calderas, can only occur in a quiet, tectonic situation on stabilized blocks or during distention. For example, a "quiet" block such as this existed in the Paleozoic in Central Kazakhstan, compressed between two belts of contiguous faults; horizontal displacements occurred along some of these. Isometric volcanic and tectonic depressions, forming as it were a continuous, large, honeycombed network, developed within this quiet block; intrusives extended along the faults, dike belts, grabens, and elongated depressions, filled with effusives, were formed simultaneously with this in fault belts fringing the block (Shcherba, 1970).

As a whole, analysis of the distribution of central and ring complexes shows that they gravitate towards quiet blocks of the shield type (Sveshnikova, 1968; Elston, 1971). Apparently, the small size of round volcanic depressions in volcanic belts (or, similarly, the regular shape of large depressions) is caused by the fact that the Earth's crust in these belts is broken up into small heterogeneous blocks.

Returning to the Moon, we see here the same tendency (although it is less manifest) and is: the smaller any dislocated region, the more volcanogenic craters tend to be circular. This work did not include examining the shape of volcanic craters depending on tectonics. But J. E. Spurr (1944-1950) has described in detail how the intensity of dislocations is attenuated as it moves away from the cordillera of Mare Imbrium, broken up by many faults, and the shape of craters varies from elongated grabens to rectangular graben-craters and so on in nondislocated regions to "normal" isometric and circular craters. Here, it is often seen that the shape of grabens and graben-craters is not caused by most recent movements, but is primary. Since intensive fault tectonics on the Moon is linked mainly only with cordilleras of round maria, a relatively stable situation is maintained on the remaining territory, and activity of magmatic foci is not subjected to "tectonic distortions."

/158

In this way, the lunar crust is more uniform than the Earth's, both in material composition and in tectonic structure. Obviously, this uniformity should cause an isotropic distribution of stresses around magmatic foci and an isometric shape of the foci themselves, which, in the final analysis, determines the rounded shape of lunar volcanic craters. Hence, the external similarity (in the first approximation) between meteorite and volcanic craters: in both cases, crater-forming forces are

are distributed uniformly on all sides -- be it the shock wave of a meteorite explosion or the pressure gradient around a magmatic focus.

Thus, one should consider the basic factors causing the specifics of lunar volcanism to be the dynamic regime of foci (determined mainly by features of the thermal history of the Moon) and the uniformity of the lunar crust with respect to its material composition and tectonic structure; furthermore, features of lunar volcanism are linked with the nature of outgassing of magmas and their effusions, which result in the first place from the smaller force of gravity.

/159

Other factors are probably active: the distention of the crust when there is maximum heating-up of the interior, the smaller lifting capacity of a melt (due to the reduction of buoyancy forces), the breaking-off of the cover of foci when a shock wave passes after large meteorites have fallen, and others. Possibly, during widespread fusion magma does not behave as in isolated foci, for example, it rises up in long narrow columns similar to saline diapirs with the formation of ring walls on the surface as above some diapirs. As yet, it is not possible to determine the significance of these mechanisms.

An approximate diagram of the interdependence of these factors can be compiled to systematize the factors affecting the features of lunar volcanism (Fig. 57). The main question which interests us is the reasons for the increased role of caldera and excavation forms on the Moon; therefore, the diagram is limited to those links which, according to the author, bring about this result (for example, processes which form radial and ring tectonics of maria are not taken into account).

Some Peculiarities of Structures on Mars

An amazing similarity between many structures of the Martian and lunar surface was observed as the result of photographs taken by spacecraft in the Mariner series. If one did not know that the Mariner photographs showed Mars, one would think that these photographs were of some parts of the Moon.

Like the Moon, Mars is covered by many craters; their frequency distribution according to diameter is similar to the analogous distribution of craters on the Moon (although it is still not clear whether the deficit of small craters is linked with the insufficient resolution of photographs or if in fact there are few of them). One can already say quite confidently that many Martian craters are primary volcanogenic formations. There are chains and groups of craters here; there are concentric and mutually intersecting craters, irregular scalloped depressions with poorly expressed walls, craters whose

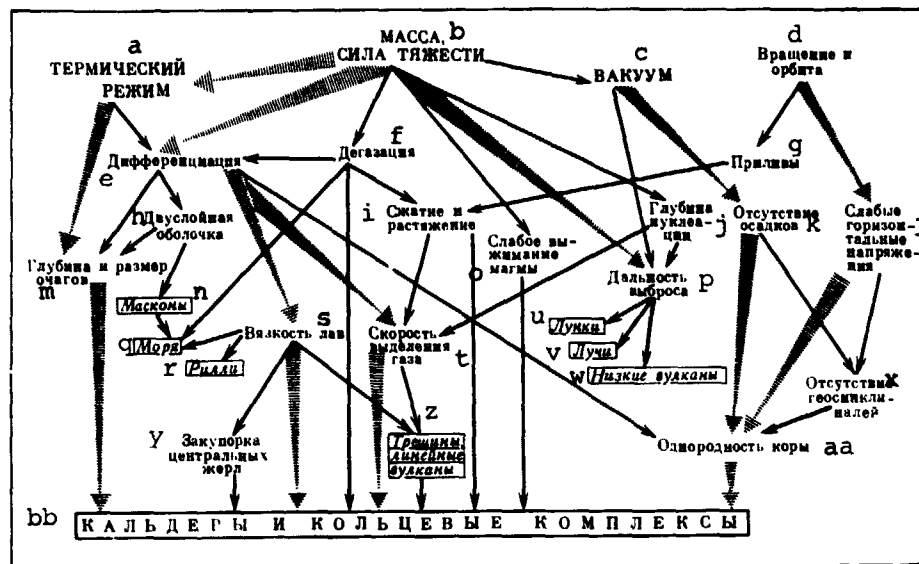


Fig. 57. A diagram of the interrelations between factors and processes causing features of lunar volcanism. Arrows show the cause-effect relationships (the determining relationships are shown by broad arrows); in the boxes are some lunar structures.

- Key:
- a. Thermal conditions
 - b. Mass, force of gravity
 - c. Vacuum
 - d. Rotation and orbit
 - e. Differentiation
 - f. Outgassing
 - g. Influxes
 - h. Two-layer shell
 - i. Compression and distention
 - j. Depth of nucleation
 - k. Absence of sediments
 - l. Weak horizontal stresses
 - m. Depth and size of foci
 - n. Mascons
 - o. Weak pinch of magma
 - p. Ejection range
 - q. Maria
 - r. Rilles
 - s. Lava viscosity
 - t. Rate of gas emission
 - u. Craterlets
 - v. Rays
 - w. Low volcanoes
 - x. Absence of geosynclines
 - y. Plugging of central vents
 - z. Fissures, linear volcanoes
 - aa. Uniformity of crust
 - bb. Calderas and ring complexes

walls continue at a tangent to rectilinear crests; accumulative cumulations (volcanoes) are seen on the crest of crater walls.

Hence, on one of the photographs, a caldera is visible with a diameter of approximately 110 km (Arskaya) with a flat floor and a sharp wall crest; the internal slopes are terraced, and the smooth external slopes at a distance of up to 40-50 km from the wall crest are broken by concentric faults and grabens; further beyond this belt there is a zone of subradial cracks, furrows and craterlet chains; to the south of the wall crest, two radial furrows approximately 70 km in length, similar to irregular chains of merging craterlets, drop down from the smooth external slope, and a similar structure is visible on the north wall. It is interesting that the external belt of radial furrows is similar to the stream-like structure of some lunar craters, but no sharp concentric grabens are seen on the Moon, and the radial furrows are somewhat similar to sector grabens of terrestrial calderas. /160

The calderas Akreskaya and Olympica (diameters 50 and 65 km) are complex "clusters" of several craters linked by common central subsidences. These formations are similar to petal-like craters on the Moon and calderas of terrestrial shield volcanoes, differing from the latter in their greater size and more complex form. Around the caldera Olympus are structures subradial to it, similar to structures on the slopes of the lunar crater Aristarchus and some terrestrial lava flows. There is a 20-km depression in the center of this caldera, very similar to the lava lake Halemaumau.

The caldera Pavlin'ya is surrounded by subconcentric arcs of grabens, fissures and typical mare ridges; the arc of mare ridges is similar in size and morphology to the lunar extrusive ring Flamsteed P.

One of the Mariner 9 photographs shows an almost straight chain of contiguous craterlets with diameters of 3-20 km stretching for more than 350 km, whereas there are hardly any craters in the vicinity. Undoubtedly, this chain traces a fault disturbance. Not far from this place, a short chain of craters continues directly in the form of a large graben.

But with all this similarity between Martian and lunar calderas, there are certain differences. Martian calderas, in general, are less regular than lunar ones; their walls are less expressed; they are not as deep; the internal slopes are poorly terraced. This makes Martian calderas similar to terrestrial ones. But the calderas Olympica, Akreyskaya, Arskaya and Pavlin'ya are on high ground with base diameters from 2⁰⁰ to 500 km and are several kilometers high (the height of Olympica is more than 6 km). It is difficult to interpret these elevations other

than as gigantic shield volcanoes; similar structures on the Moon are on a much humbler scale.

As on the Moon, on Mars there are extensive regions of areal effusions: flat plains with ingressive contacts, and often the material of the plains overlaps walls of older craters. Very characteristic mare formations are visible among these plains: rilles and mare ridges. There are also several large concentric structures of the thalassoid or ring mare type. The density of craters on the maria is much less than on highlands.

However, there are obvious differences between Martian and lunar maria. The edges of round maria do not form high, raised cordilleras, but are simply a somewhat elevated and dislocated zone. Lavas forming maria apparently are not as fluid as on the Moon: even when the Sun is high, marginal scarps of individual flows are clearly visible (two such flows have diameters of approximately 100 km). Finally, Martian rilles are certainly not simple lava drainage channels -- their length reaches 400-700 km, and they are 20 km and above in width, that is, greater than Schröter's Valley, and they are definitely subordinate to tectonic control. As yet it is difficult to say with sufficient certainty, but the absence of cordilleras and the great viscosity of lavas makes Martian maria similar to terrestrial traps. (It must be noted that the interpretation of Martian maria is still quite problematic, and is linked with the possible intensive reworking of Martian structures by exogenous processes. Thus, it was found that dark areas on the flat floors of some craters consist of sand dunes, not young lavas, as on the Moon.)

/161

Finally, on Mars there are definitely structures formed by horizontal stresses, and these stresses are localized in certain zones. In the south polar region, a whole zone of narrow, parallel grabens and horsts was photographed. A system of gigantic rifts, with an overall length of approximately 3500 km and a width of 100-200 km, passes along the equator, and, besides this, there are areas of less regular graben-like subsidences and cracking, also undoubtedly linked with distention. Where the grabens converge and taper away, there is a so-called chaotic relief -- an area of haphazardly mixed, apparently fragmented blocks, similar to badlands: this relief probably shows areas where distention has not reached the stage of clearly expressed grabens. This relief is seen in other places.

It is true that until now no compression structures have been observed on the photographs available. Fan-like and subparallel curved strips in regions near the poles, similar to diagrams of folded structures, when examined more closely prove to be cuesta-shaped scarps along the rims of flat, stratified plateaus. Not all the surface of Mars was photographed, and by no means all available photographs have been processed.

Thus, with all the similarity of Martian structures to lunar ones, some features of these structures are closer to terrestrial formations; probably, this is somehow linked to the fact that Mars occupies an intermediate position between the Earth and the Moon, first of all in mass. Of course, it must be stressed that this conclusion is only of a purely preliminary nature. But, in any case, the "intermediate" morphological characteristics of Martian structures, in the future, will allow for a more reliable comparison between terrestrial and lunar structures.

Conclusions

Thus, the following conclusions can be made on the basis of geological and morphological interpretations of photographs at our disposal.

I. The following volcanic features are widespread on the Moon's surface.

Domes. Flat, rounded elevations shaped like a shield or a round loaf; their diameters are from hundreds of meters to 5-15 km, sometimes greater; their height is from several tens to several hundreds of meters. They are found mainly on maria and on flat crater floors. They are interpreted as lava domes and shield volcanoes; possibly, some are laccoliths.

Central volcanoes. Isometric, elongated, light knolls and peaks of conical or irregular shape, often with summit craters. The diameters of their bases are from several hundreds of meters to 30-40 km, in some cases up to 60-80 km; their height is from several meters to 1-2 km, and occasionally greater. They are recognized by their interrelations with surrounding structures (overlaps) and by their shape; there are more of them on highlands than on maria. A link has been found with linear structures: mare ridges, cordilleras, crater walls, fissures and ridges. Among them are central peaks of cirques: displaced from the center, elongated, with summit craters or consisting of several peaks.

Dikes and volcanic ridges. These are mare ridges (elevations above sills, stretching along faults); crests, intersecting crater walls; crests, continuing crater walls at a tangent; central ridges in craters. Their width is from a few kilometers to 10-15 km, their height from tens to hundreds of meters. Besides sills there apparently are linear extrusions and merging chains of volcanoes. /162

Extrusions. Light, rounded knolls, similar to central volcanoes; they are recognizable by their characteristic small ridges near the base, and are interpreted as accumulation of extrusive breccias.

Regions of areal effusions. Young maria, according to information available, formed mainly by flows of basalt-like rocks with interbedded pyroclastics. Probably, the lavas of ancient maria are similar to young lavas, although it is possible that here there are more acidic varieties; it is also possible that there are ignimbrites. Besides large mare basins, lavas fill the floors of the majority of craters with a diameter greater than 15-20 km, many small basins on the highland relief, and are also seen in sinkholes on the internal and external slopes of crater walls.

Volcanic regions. Mare regions (predominantly ancient mare), covered by many small knolls (volcanoes and cinder cones), chains of craterlets, fissures, furrows and ranges. The complexity of structures in these areas makes it impossible to separate endogenous and exogenous forms.

Craters of volcanic origin. They are recognized by the following indications:

- 1) distribution: groupings of similar craters in chains, pairs and clusters when there are no craters of similar structure and size in the vicinity, the conformity of craters of similar formation to determined zones;
- 2) structure: concentric structures of decikilometer craters, structural interrelations and mutual intersections of adjoining craters;
- 3) the nature of the wall: sharply polygonal, elongated and scalloped walls, the disparity in the width of the wall with crater dimensions; smoothed slopes of young crater walls.

The lava floors of craters, cinder cones and individual volcanoes on the floor and on the walls, terraces and gothic structures are seen both in volcanogenic and in meteorite craters reworked by volcanism.

There is no single indication allowing one to classify all volcanogenic and meteorite craters and all accumulative and tectonic elevations. The question of the origin of one or another lunar structure must be solved using several indications.

II. The following varieties can be approximately separated among volcanogenic craters.

A. Concentric craters. The internal part is filled with concentric walls, crests, fissures and furrows, and vertical movements are seen along these; an accumulative (extrusive?) origin has been determined for some crests. Their size is from 20 to 100 km; apparently, concentric craters less than 20 km are formed

from several explosive craters laid one on the other. They are localized mainly on the edges of maria.

B. Primitive rings. Round and oval systems of mare ridges (dikes and sills), low, broken, smoothed ranges (extrusions and volcanoes), with diameters from 10-15 to 100-150 km. They are seen predominantly in maria. /163

C. Mature craters. Cup-shaped craters with a flat floor, terraced, with visible lava flows; the crest of the walls is sharp, and the external slopes are smooth. The latter, together with their distribution in pairs, distinguishes them from meteorite craters. Diameter 25-50 km.

D. Petal-like craters. Basins with a low, narrow wall without terraces; in plan, the crest of the wall is slightly undulating or scalloped, sometimes rectangular. The floors are flat and covered with small ridges. The diameters are 5-30 km; there is a tendency for these craters to group into "clusters."

E. Explosive craters. Cup-shaped craterlets up to several kilometers in diameter, linked with mare ridges, faults, grabens, joined into rectilinear chains (distributed in isolated fashion or linked with the tectonics of the area), confined to volcanic cones and domes. There are two transition varieties between craterlet chains and grabens -- excavation trenches (grabens, reworked by volcanic explosions and subsidences).

F. Complex cirques. Large (up to 150 km) ring structures with massive, smooth walls on which there are individual volcanoes and lava lakes; the extensive lava floors contain complex central peaks, central ridges, fissures, rilles and ghost craters. The crater walls reveal a close link with the tectonic structure of the adjoining area.

III. Meteorite craters differ from volcanic, isometric ray systems, since they extend from tens to hundreds of kilometers and have a flow-like and dune relief of the external slopes and swarms of secondary impact craterlets.

All craters with a diameter larger than 25-30 km have to some extent been reworked by volcanism. Volcanic manifestations are not seen as often and almost disappear in craters smaller than 10 km among meteorite craters with small diameters.

The theory of volcanism initiated by meteorite impacts requires such shallow stratification and such large volumes of magma that mass manifestations of "natural" volcanism of the caldera-forming type are unavoidable.

IV. Meteorite craters on the Moon are found mainly in the interval up to the first few kilometers, where they form a great majority. Volcanogenic craters with a diameter above 20 km are comparable in numbers with craters of meteoritic or unknown origin, making up 10-20% of all craters in this range.

As a whole, volcanogenic craters occupy approximately from 3-5 to 9-12% of the lunar surface, regions of areal effusions and volcanic regions up to 30-35%, volcanoes and extrusions from 0.5 to 1-3%; in total, this gives from 33.5 to 50%, and there is basis to believe that the whole lunar surface in former times passed through the stage of volcanic reworking.

V. The basic differences between lunar and terrestrial structures leads to the increased role and the greater scale of negative forms (excavation and subsidence) on the Moon, with a smaller number and size of accumulative formations of the central type. On an average, lunar calderas are larger and deeper than terrestrial ones, with more powerful ring complexes, and their central volcanoes are of subordinate significance. Lunar volcanoes are smaller than terrestrial ones, and when their diameters are similar they are lower; on the Moon there are more explosive craters similar to maars. Unbroken volcanic ranges and ridges are developed much more widely on the Moon than on the Earth. /164

By allowing for these differences one can, in the first approximation, note the conformity between terrestrial volcanic craters and calderas and lunar volcanic craters:

A. Terrestrial ignimbritic depressions and ring complexes are most similar to concentric craters and complex cirques on the Moon.

B. Primitive rings on the Moon are analogs of terrestrial ring dikes.

C. On Earth, calderas of the Krakatoa type (explosions with collapses) correspond to mature lunar craters and craters-craterlets with a diameter of up to 10-15 km.

D. Terrestrial calderas of the Hawaiian type (subsidence due to drainage of magma into lateral channels with peripheral effusions) are similar to petal-like craters on the Moon.

E. Explosive craters on the Moon are similar to terrestrial maars and multiple-action vents.

VI. The differences between terrestrial and lunar volcanism can be explained by the following reasons:

1. the thermal history of the Moon, the specifics of which are contained in the generation of large amounts of magma at

early stages of the Moon's development. The universal distribution of extensive lava fields and volcanic craters indicates a period of intensive fusion of the lunar interior. Apparently, many large, magmatic foci near the surface were formed here when it was heated up most. The rapid effusions of large volumes of magma from these foci formed many large calderas.

2. the uniformity of the lunar crust, composed mainly of basalt-like rocks, gabbro and anorthosites with interbedded pyroclastics and meteoritic and explosive deposits; the relatively uniform distribution of stress in the crust; the poor development of horizontal movements. As a result of this uniformity, the distribution of stresses over the magmatic foci should be relatively isotropic, which makes it easier for circular forms to occur with the predominant role of vertical movements.

3. the reduced force of gravity, resulting in the fact that volatile components were separated at greater depths and volumes in comparison with terrestrial conditions; probably, this increased the explosive nature of eruption. Pyroclastic fragments covered a great distance due to the reduced free-fall velocity, were not slowed by the atmosphere and were accelerated by an additional cloud of volcanic gases expanding freely in a vacuum after the explosion. Therefore, on the Moon there are more explosive craters and fewer volcanic cones, and the latter differ from terrestrial ones in their smaller size.

4. differentiation features of magmas caused by a more rapid outgassing, lower pressures, a smaller force of gravity and an absence of a sedimentary and granite crust which could contaminate basalt-like melts. Hence, the different composition of effused products and a different type of effusion, creating the specific appearance of lunar volcanic forms.

Obviously, many other factors are active, but it is still difficult to estimate their role.

VII. During further research, one must clarify the boundaries /165 for the applicability of criteria of volcanic origin used here for forms of a different scale and age, and also attempt to find additional criteria of this type. A method must also be developed to determine the relative age of volcanogenic formations on the lunar surface. The solution of these questions will make it possible to definitely evaluate the number and distribution of volcanogenic forms on the Moon, and also make conclusions on the evolution of lunar volcanism and differences in the formation of highland and mare regions and smaller regions of the lunar surface.

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THE GEOLOGY OF LUNAR MARE BASINS
(V. G. Trifonov)

The Subject of Study, Terminology, Morphology and Systematics

/174

The work is devoted to showing the nature of the basins of lunar maria and features of their structure. Until now, there have been two basic concepts of the origin of these structural forms. Some researchers link their formation to the fall of large foreign bodies onto the Moon's surface; others believe that the mare basins are a manifestation of the Moon's internal activity.

Supporters of the first theory, predominantly astronomers, base their conclusions on the morphological, geometrical peculiarities of the Moon's circular maria: the rounded outlines, the shape of structures on the edges and radial and concentric disturbance systems. These indications were formulated by the founders of this concept (Gilbert, 1893; Baldwin, 1949) and later were made more precise and extended to the whole visible part of the Moon (Hartmann, Kuiper, 1962; Hartmann, 1963; Yuri, 1963; Hartmann, Wood, 1971). In essence, the concept examined is based on several analogies of circular mare basins of the Moon with natural and experimentally produced impact and impact-explosive craters on Earth.

The second concept is defended mainly by geologists who have studied the structure of the lunar surface (J. E. Spurr, A. V. Khabakov, von Byulov and others). J. E. Spurr (1944, 1945), noting several features of the relief of lunar maria and bordering highland formations and their partial analogies with volcanic forms on Earth, compiled a somewhat speculative diagram for the formation and development of mare basins as manifestations of tectonic and magmatic processes on the Moon. Only A. V. Khabakov (1949, 1960) used the fact of the geologic history of lunar maria to explain this problem by drawing attention to the fact that the prolonged development or almost instantaneous formation (in the geologic sense) of lunar mare basins was the main indication of their endogenous or exogenous-impact origin.

At the present time, most researchers have a divided opinion on the volcanic origin of lunar mare material and, by the same token, the unsolved problems of the nature of lunar maria lead to questions of the formation of the basins themselves and structural forms associated with them. The present work is aimed at attempting to answer these questions, where the author, developing the ideas of A.V. Khabakov, examines mainly the geologic history of these structures.

Until recently, all, and now many, selenologists only understand as mare material rock complexes of plain regions of the lunar surface with relatively low albedo (normally lower than

0.08), which have been called Procellarum (Shoemaker, Khekman, 1963). J. E. Spurr noted the possibility of separating mare formations into two groups according to their relationships with ray systems of young craters, where the younger group is characterized by lower albedo. Detailed research, conducted in connection with the compilation of geologic maps of the Moon on a scale of 1:1,000,000 allowed American researchers (Moore, 1965; Carr, 1966; McCauley, 1967; Titley, 1967; Morris, Wilhelms, 1967; Schaber, 1969; and others) to divide the Procellarum into four subcomplexes. Side by side with these, younger mare formations have been isolated, corresponding in age to crater complexes -- Eratosthenian: dark material in the Littrow fissure region and the Tacquet formation (Carr, 1966), the Marius group (McCauley, 1967), the EJM mare formation (Schaber, 1969; Ulrich, 1969), and the Copernican: the CEM mare formation (Wilhelms, 1968). The formations of Sulpicius Gallus (Wilhelms, 1968), Harbinger (Moor, 1965) and Doppelmayr (Titley, 1967), completely or partially coinciding in age with the Eratosthenian craters, are similar to mare formations, although they differ in some relief features. /175

Such a fractional partition of the Procellarum complex is not always correct, since the conclusions on the relative age of subcomplexes, based on different albedo and density of crater cover, is hardly corroborated by information on structural and geologic relationships. At the same time, the Procellarum can be broken down into two parts with sufficient certainty in many places of the Moon's visible hemisphere. It is also valid (Markov et al., 1972) to separate the youngest mare formations, having an albedo of approximately 0.06 and overlapping ray systems of early Copernican craters, from the composition of the Procellarum complex.

The relative age of this young mare complex corresponds to the CEM formation. The relationships with the Eratosthenian mare formations, isolated by American researchers, is more complex. Some of them, as it were, run parallel to a complex of the youngest mare formations (at least, part of the Tacquet and Sulpicius Gallus formations). Attempts to correlate mare formations over the whole visible hemisphere make very likely the parallelization of the EJM formation, material of the Littrow fissures region and, possibly, the Marius group with the youngest members of the Procellarum complex. The upper Procellarum complex is, in this way, partially synchronous with Eratosthenian craters. Its boundary with the lower Procellarum subcomplex corresponds approximately to the boundary of two upper and two lower subdivisions of the American researchers' Procellarum group. Old members of the Procellarum complex section are probably partially synchronous with the Archimedian crater complex.

In 1936 M. Ewen and, later, A. V. Khabakov (1949) noted a similarity between the surface and structural position of the highland plain to the southwest of the Altai scarp and lunar maria,

which gave A. V. Kahabakov the basis for isolating ancient Altaic mare formations. A. L. Sukhanov (1969b) showed the distribution of ancient maria on the whole near side of the Moon and examined in great detail the reasons for the differences between their albedo and the nature of the surface and the mare rocks of the Procellarum complex, having linked these differences with more recent transformation of the surface of ancient maria. With more detailed mapping of the equatorial region of the visible hemisphere, old mare formations were divided into Median and Altaic rock complexes; this revealed mare rock of part of an older Nebular complex (Sukhanov, Trifonov, 1969)¹.

/176

Now there is more data on the fact that the Procellarum formations are of different ages in various parts of the Moon, and their formation covers a considerable time interval (see the section "Multistage Development as a Reflection of the Long-Term One") corresponding to the formation of Eratosthenian, Archimedian and, partly, Ptolemaic craters. At the same time, in a number of cases, the relationship between light maria formations and craters and faults disturbing them allows one to assume the relatively young age of some light formations. Apparently, in some places dark (Procellarum) and light (Median and Altaic) mare formations can be of the same age, although, normally, light formations are older.

In this work, by mare formations we also mean relatively young and old mare complexes. This allows us to examine thalassoids ("Atlas of the Far Side" ... 1967) as basins, completely or to a considerable extent made up of old mare formations.

Mare complexes on the Moon's surface form small patches and extensive fields of an irregular shape (in both cases, regions where mare rocks emerge are quite shallow relative to adjoining

¹ Highland plain formations, similar to the Procellarum mare complex, but covered by a large number of craters, were also isolated by American researchers. As opposed to ancient mare complexes on our scale, these formations were not correlated among themselves. Apparently, the formation of highland plains Ip (Shoemaker et al., 1966; Schaber, 1969; Ulrich, 1969), the Cayley formation (Morris, Wilhelms, 1967; Milton, 1968; Wilhelms, 1968) and the "Apennine Bench" formation (Hackman, 1966) correspond completely or partially to the Altaic mare complex. In a number of places, these formations are broken down according to the degree of destruction and density of crater cover. Material from the Kant plateau with its gentle hilly surface (Milton, 1968) corresponds to older, probably Nebular, mare formations. On the American scale, there are no analogs of rocks of the Median complex. They are partly attributed to the lower subdivision of the Procellarum group, and probably partly included in the composition of the youngest members of the highland plain formation.

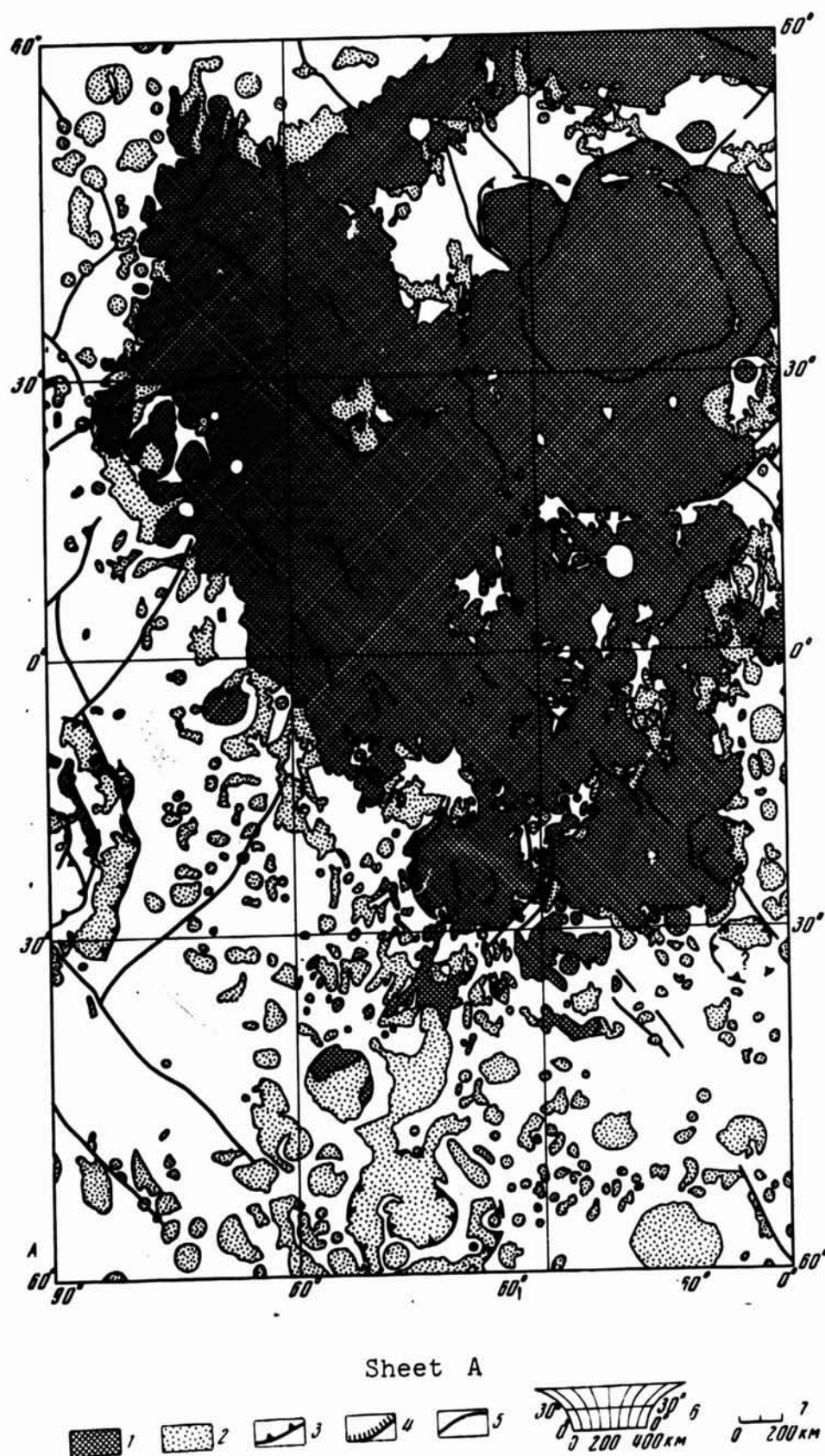
areas, and there is a complete range of transitions between both types of basins, which makes it possible to investigate them as a single structure type). They also fill the floors of some craters and basins of circular maria. A large number of relicts of older craters and structural forms outside of craters can be seen emerging above the surface of mare rocks in irregularly shaped maria. When there is a layered or lenticular stratification of mare material, which, according to geologic interpretation of photographs, is more probable for the majority of mare formations, it is possible to approximately calculate the thickness of mare rocks (Sukhanov, Shkerin, 1969). Similar relationships are seen comparatively rarely in circular maria: only near the edge and sometimes around internal cordilleras. Probably, the thickness and corresponding overall volume of mare complexes in circular maria is significantly greater than in irregularly shaped maria and small exposures of mare material. Therefore, round maria, whose origin was the subject of the discussions mentioned at the beginning of this work, will be investigated in particular detail.

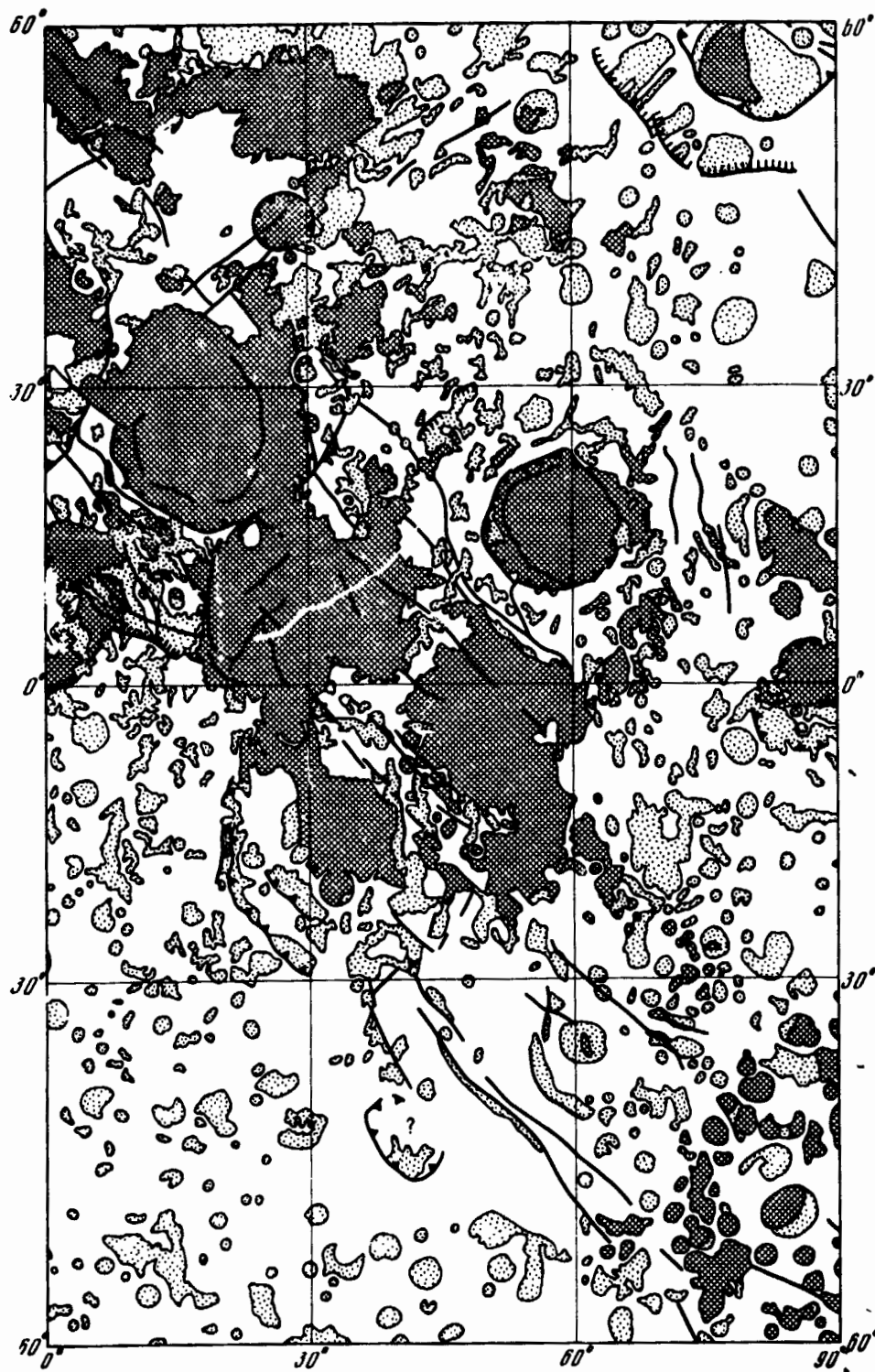
Strictly speaking, these structural forms can only be called round arbitrarily, since the outlines of many maria are polygonal to a greater or lesser extent. The boundaries of basins are everywhere, and more often are represented at a considerable distance by marginal cordilleras: asymmetric crests with a steep slope facing the mare and a more gentle external slope. The steepness of the internal slopes can reach 30° (Apennines). Sometimes this scarp divides into two and, between its branches, there is a bench, horizontal or inclined from the round basin (the eastern boundary of Mare Imbrium, the western boundary of Mare Crisium, and the Altai scarp).

/177

Gradually descending from the circular basin, the external slope of the cordillera is frequently replaced by basins, sometimes elongated and extending approximately along the boundaries of a circular mare. These basins are grouped into a peripheral belt of maria, forming arcs and, to a lesser extent, rings around circular basins (Fig. 1). An immense belt surrounds Mare Imbrium, taking in Mare Frigoris, Sinus Roris, the northeastern part of Oceanus Procellarum, the northern part of Mare Nubium, Sinus Medii and Sinus Aestuum, Mare Vaporum, a field of mare formations of different age to the north and south of it, and, finally, is lost in the circular basin of Mare Claritas.

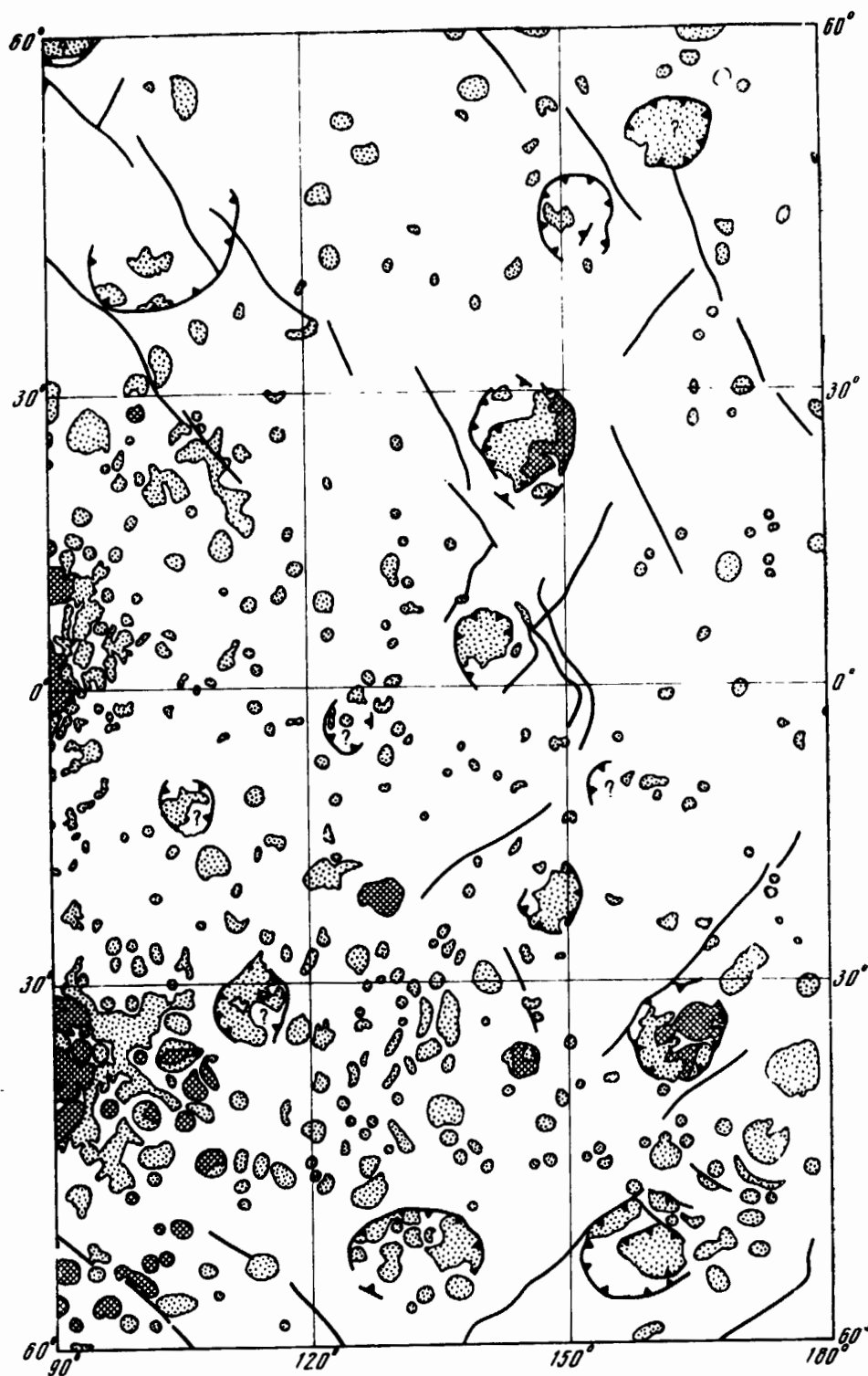
Frequently, a belt of peripheral basins is divided into several branches (Sinus Aestuum and Sinus Medii) or peripheral basins grouped into several belts. Thus, there are no less than two belts to the north and south of Mare Crisium. By no means do peripheral belts always form concentric systems with centers in the middle of maria. Their distances from the center of a circular basin and the width of individual basins of the belt





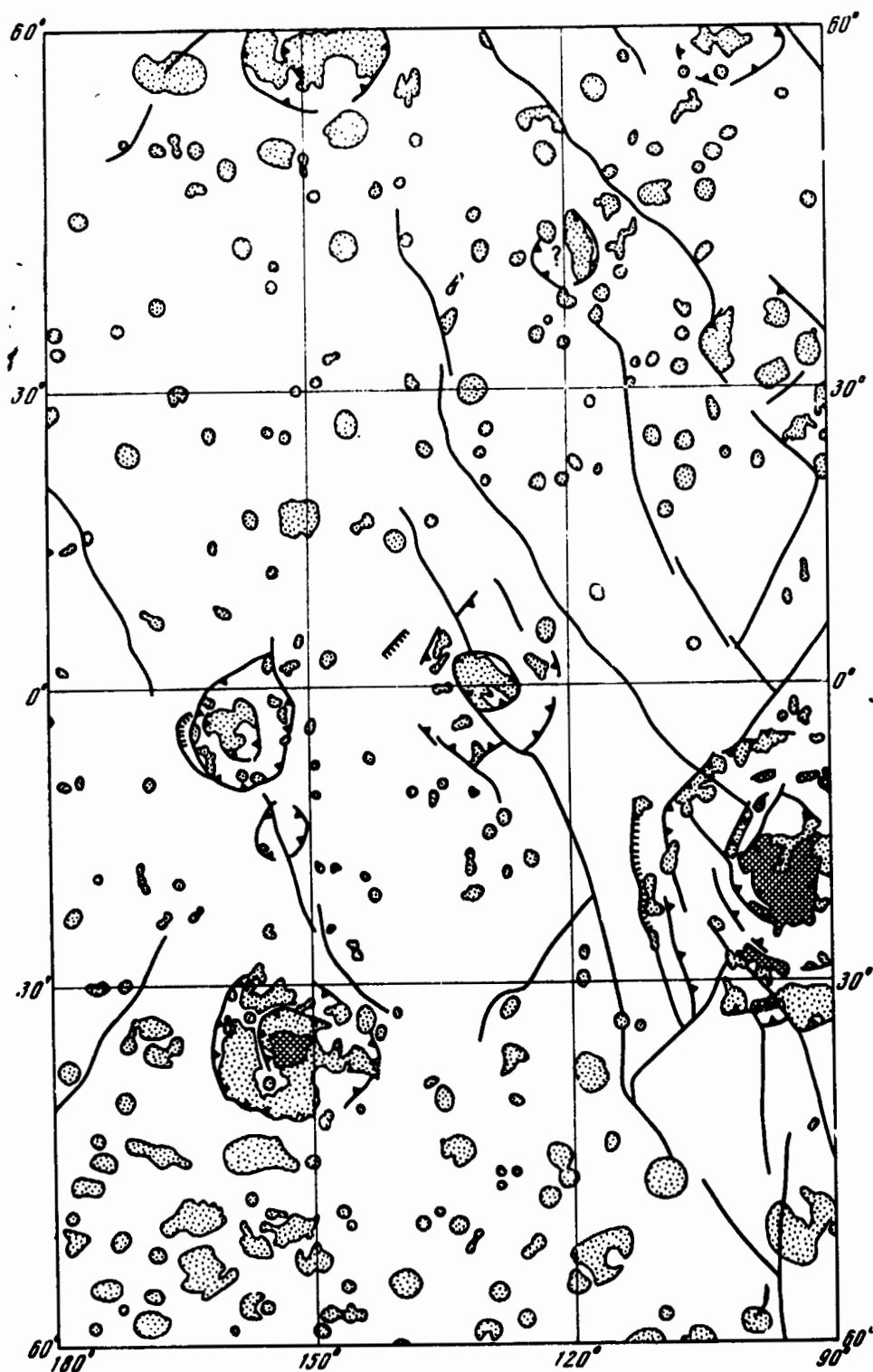
Sheet B

Fig. 1 (cont.) and structural elements of the Moon linked with them. 1. Procellarum and younger mare formations; 2. Altaic and Median formations; 3. benches of marginal cordillera; 4. fault boundaries of the peripheral belt of basins; 5. some large fractures of other systems; 6. scale for latitudes 0-60°; (cont.)

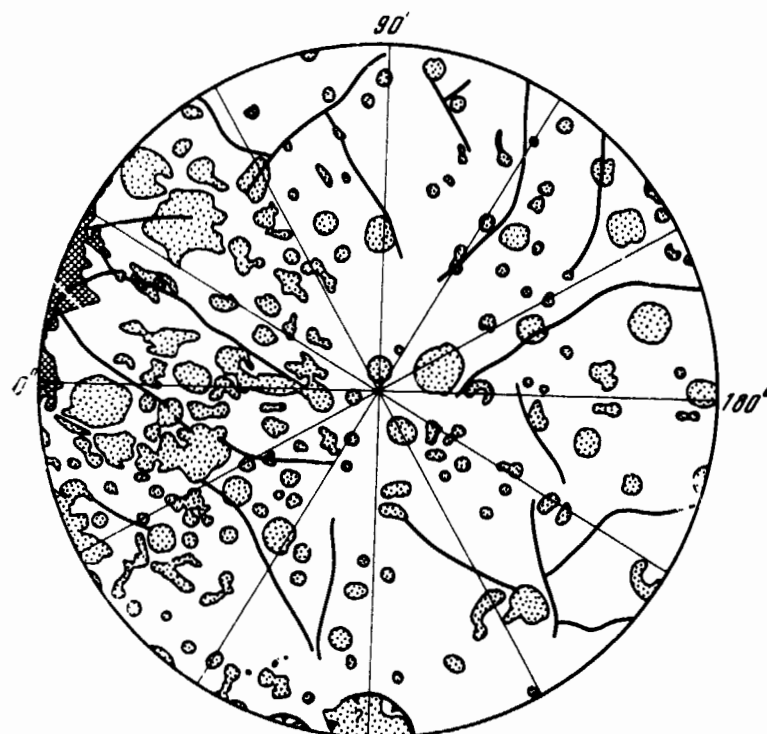


Sheet C

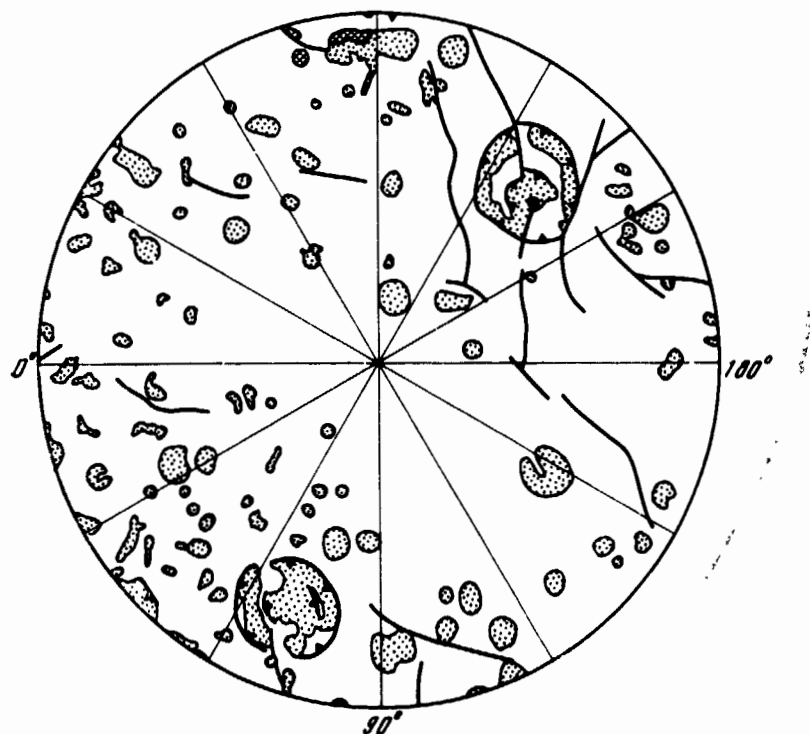
Fig. 1 (cont.) 7. scale for latitude 60-90°. A-E, sheets of the diagram (A, B - near side; C, d - far side; E - northern polar region; southern polar region).



Sheet D



Sheet E



Sheet F

can vary. Cases have been known in which the center of a ring of peripheral basins does not coincide with the center of the circular basin. The boundaries of basins of a peripheral belt are normally uneven. The external boundaries are sometimes limited by scarps of the cordillera type. There is such a basin scarp of Altaic age between Dionysius and Ukert (Trifonov, 1969a). There are no reliably known scarps on the internal rims of basins.

The internal area of round basins is relatively even; however, there are ring elevations of the cordillera type. In the Mare Orientale region, they form three almost regular concentric rings. Two less well-expressed rings are visible around Mare Nectaris, inside the Altai range cordillera. In Mare Imbrium, traces of this cordillera are marked by individual peaks and a complex system of mare ridges. The internal zone of the mare outlined by them is displaced to its northwest rim. A similar system of scarps, ridges and arched faults bound the internal zone of Mare Crisium, displaced to its southern rim. There is an arched system of ridges and faults generally parallel to the marginal line in Mare Humorum and Mare Claritas. According to W. K. Hartmann and J. A. Wood (1971), concentric and arched structures inside circular basins (internal cordilleras, systems of peaks and craters, graben-shaped depressions) at least partly, have a tectonic and volcanic origin.

It is sometimes difficult to show the boundaries of a circular maria when there are several ring elevations around and inside the basin. In these cases, we accept the highest and most clearly expressed cordillera as the mare boundary. Because of this, in some cases it was necessary to change the accepted names. Hence, the Altai range became the boundary of Mare Nectaris, and the Cordillera range became the boundary of Mare Orientale, which included the arched mare basins of Veris, Autumni and Pacis.

A circular mare basin, the main cordillera around it, ring and arc elevation on both sides of the cordillera and belts of peripheral maria are a characteristic combination (paragenesis) of structural forms, repeated to a greater or lesser extent in all circular mare basins of the Moon.

/178

The question of relationships between circular mare basins and faults requires special examination. The link between circular maria and concentric, that is, ring and arc disturbance systems parallel to the edges of maria, as it were, does not give rise to doubt. So-called radial systems cause more complications. They were first noticed by G.K. Gilbert (1893) for Mare Imbrium and were further substantiated by Hartmann and Kuiper, who classified practically all large fault disturbances of the lunar surface as radial or concentric systems (Hartmann, Kuiper, 1962; Hartmann, 1963).

Other researchers (Khabakov, 1949, 1960; Fielder, 1963) showed the discrepancy in the strikes of many faults, with radial and concentric directions, especially at a distance from mare basins. G. Fielder recognizes that there are radial faults on the Moon, but, at the same time, also notes the general planetary disturbance systems, not linked with the disposition of individual mare basins: northwest, northeast, and, to a lesser extent, meridional. The absence of quantitative indices leaves it unclear whether G. Fielder has in mind sufficiently localized maxima of strikes or only the directivity of faults in those or other directions. In the latter case, it is apparently impossible to speak of the planetary orderliness of fault disturbances.

The number of faults of different strikes in the region near the visible hemisphere of the Moon was calculated to solve the problem of the laws governing the arrangement of faults (Trifonov, 1969a; Sukhanov, 1969c; Salisbury et al., 1965; see also Fig. 6 in this work). The calculations showed the presence of sufficiently local maxima of strike: the northwest and northeast and meridional subordinate to it. The quantitative relationships between them varies from area to area, but the orientation remains approximately identical. A review of other areas of the Moon shows that this tendency is maintained, that is, the presence of a network of fault disturbances is general for the whole planet surface oriented relative to the rotation poles in an orderly fashion. In cases where the faults are actually radial to the basins of lunar maria, this is not a continuous uniform fan of linear disturbances; faults which coincide in direction with the planetary maxima mentioned above (the southeast and south margins of Mare Imbrium, Mare Nectaris and Mare Orientale) predominate and are of the greatest extent.

/184

Geologic interpretation of photographs of the lunar surface also showed that by no means all mare basins or sections of basins are characterized by radial and concentric disposition of faults on the margins. They often abut at acute angles or are at a tangent to the boundary oval of the basin, maintaining one of the planetary directions (the north margins of Mare Orientale and Mare Imbrium, Mare Crisium).

In spite of the planetary orderliness of fault distribution, their number increases as they approach circular mare basins. This indicates the paragenetic links between basins and fault disturbances. It is also confirmed by the fact that rectilinear sections of polygonal basin boundaries have the same directions and are frequently found directly on the prolongation of faults.

The presence of paragenetic links between circular mare basins, marginal and internal cordilleras, peripheral belts of basins and fault disturbances on the Moon makes it possible to examine the development history of paragenetic members in their mutual link and judge the evolution of others by the development

of some members. Therefore, in this work we shall touch upon questions of geology of marginal cordilleras, fault systems and other structural forms associated with them to explain the history of the formation of mare basins on the Moon.

The diameters of circular lunar mare basins on the Moon vary between 1100 (Mare Imbrium) to 140-150 km (Lacus Mortis, the smallest thalassoids on the far side). In size, the latter are similar to the largest craters (Clavius, Schickard, Humboldt, Grimaldi). In connection with this, the question arises of the structural differences between mare and crater forms. There are no universal criteria, but study of a large number of these and other structural formations makes it possible to show signs which, if not always expressed, are expressed sufficiently often. For the most part, large craters have more or less distinct walls which protrude above the floor and above the surrounding area. A marginal cordillera is only clearly raised above the floor of a mare basin, and its external slope is so gentle and badly deformed that its boundary can only be shown arbitrarily.

Faults of a marginal cordillera are mainly grouped into systems of specific strike and, intersecting or dividing each other in places, prick out angular blocks of rocks. Similar disturbances are seen in large craters (Clavius, Riccioli), but concentric ones are more characteristic of them (Petavius, Clavius, the crater between Nansen and Mare Moscovienne) and, to a lesser extent, radial (Humboldt, Petavius, Tsiolkovsky) disturbance systems. Crater chains are often found along concentric faults. Regions adjoining many large mare basins are condensation regions of a fracture network. This phenomenon is not seen for large craters or it is not sufficiently expressed. Peripheral belts of basins around craters are unknown. Internal concentricers, although they are seen (Xenophanes), are the exception rather than the rule. In spite of the indications listed, in some cases it is difficult to distinguish between a mare basin and a large crater, especially if the latter is an old formation and has been greatly altered by subsequent geologic events. Examples of these are Nansen, Belkovich and Landau. The distribution of mare formations of different ages is shown on the complete structural and geologic map of the Moon on a scale of 1:10,000,000 (Fig. 2, Table 1). The principles for compiling similar charts were developed by A. L. Sukhanov and the author (Sukhanov, Trifonov, 1967, 1969). These principles are based on explaining the relative age of adjoining rock complexes making up different structural forms, insofar as their surface is disturbed by small craters and faults, just as the structural elements of the surface of one complex (for example, faults) come to an end on the boundary with other and so on. The morphological surface features of any complex allows one to trace its spatial distribution.

/186

TABLE 1. CHARACTERISTIC INDICATIONS OF LUNAR ROCK COMPLEXES

Rock types	Rock complexes	Nature of surfaces (interpreted signs)
Mare formations	1-2. Procellarum complex (Pr) and a complex of youngest mare formations (M)	Relatively even surface, variegated with fissures, craters and crater-like depressions of various size. Low ridges, domes and their accumulations are discernible. The albedo is low. Early Procellarum, late Procellarum and the youngest mare formations are distinguished according to the degree of disturbance, albedo and relationships with craters of Copernican and Eratosthenian complexes. The younger the rocks are, the less disturbed and darker is their surface. Early Procellarum formations are overlapped by the ejecta of the craters mentioned. The youngest mare formations interrupt the rays of early Copernican craters. Late Procellarum formations occupy an intermediate position.
	3. Median complex (Md)	The intermediate position between the Procellarum and Altaic complexes is occupied according to the degree of disturbance of the surface and albedo. Mare ridges are well expressed.
	4. Altaic complex (Al)	On an average, the density of covering craters is several times higher than on the Procellarum surface. There are more disturbing faults and fissures. Mare ridges are only seen in the form of relicts. As a whole, the surface preserves the nature of a plain. The albedo is medium, rarely high.
Partial mare formations	5. Nebular complex (Nb)	There are more knolls than on the Altaic surface. The number of disturbing faults increases. In places where they are most widespread, the relief becomes mountainous. There are significantly more large craters than on the Altaic surface. Small craters cannot be counted. The albedo is high, sometimes medium.

[continued]

TABLE 1 (continued)

Rock types	Rock complexes	Nature of surface (interpreted signs)
Partial mare formations	5. Nebular complex (Nb) [continued]	The nature of the surface and relationships with pre-Hipparchian craters in places where there are weak disturbances makes it possible to assume that rocks have a mare origin, but it is too early to extend this to the whole complex.
Crater formations	6. Copernican (Cp) and Eratosthenian (Er) complexes	The morphology of crater formations is clearly visible. The albedo is high to medium. Copernican craters differ from Eratosthenian rays by the preserved nature of ray systems; however, the presence of rays does not necessarily mean that they belong even to youngest craters.
	7. Archimedian (Ar) and Ptolemaic (Pt) complexes	Crater forms are frequently distorted by subsequent processes. The Archimedian formations are better preserved than the Ptolemaic. The albedo is high or medium.
	8. Hipparchian complex (Hp)	The details of initial crater formation are preserved in the form of relicts. The albedo is medium, and at times high.
Formations inside and outside of craters	9. pre-Hipparchian craters (Php); hypothetical ancient formations outside of craters (Ant); sections of the youngest complexes, transformed by more recent processes.	Badly disturbed by subsequent processes. Albedo is high or medium.

The map was compiled by the author in 1970 by interpreting telescopic photographs and images obtained using spacecraft. These photographs and images, in all, cover more than 95% of the Moon's surface. The "Complete Map of the Moon," compiled under the direction of Yu. N. Lipskiy (1969) and the "Complete Map of

the Moon" ("Lunar earthside map ...", 1970), kindly lent to us by D. Allenby, were used as a topographic base. Geologic and morphological maps of the equatorial zone of the near side of the Moon on a scale of 1:1,000,000 (Markov, 1969; Sukhanov, 1969a; Trifonov, 1969a; Florenskiy, 1969; Markov et al., 1972), a formations chart of the Moon's relief (Khabakov, 1960), an arrangement diagram of present-day and ancient maria on the Moon's near side (Sukhanov, 1969b) and other material were used to compile the present chart. Sections of the chart, compiled according to information by M. S. Markov, A. L. Sukhanov, P. V. Florenskiy and L. M. Shkerin, are shown in the legend to Fig. 2.

The age legend of the complete structural and geological lunar map is somewhat simplified in comparison with versions suggested earlier for larger-scale maps.. In part, this was caused by the desire to keep the map free of excessive details, but mainly the impossibility of showing the detailed age differentiation of rock complexes in marginal sections of the Moon's near and far sides. In particular, the fact that there are no satisfactory photographs of these areas, taken at a full sun angle, makes it difficult to distinguish between Copernican and Eratosthenian crater complexes and the age differentiation of Procellarum formations. The understanding of the age volume of an ancient rock complex also varied. Mapping of large territories showed that, besides really old craters and rocks outside of craters, younger formations, which had undergone substantial deformations and reconstruction, could also possibly be included in it. In particular, some sections of marginal cordilleras, to a greater or lesser extent, are compared with relatively young formations (Hartmann, Wood, 1971; and a section by A.L. Sukhanov in this book). They are partially shown in this map, but to a considerable extent are included in the composition of the oldest, and, to a lesser extent, Nebular rock complexes.

/187

The work consists of a geologic description and substantiation of the multistage development of mare basins, analysis of the length of these stages and the distribution of mare basins on the Moon's surface, and an examination of questions of origin of the basins and mare material adjoining them. For convenience, the circular mare basins described are divided into the following three groups:

1. basins, the surface of which is completely or almost completely formed of Procellarum and younger mare formations (of the Mare Imbrium type);
2. basins whose surface is only partially covered by a Procellarum complex (of the Mare Nectaris type);
3. basins completely composed of old mare formations (of the Korolev thalassoid type).

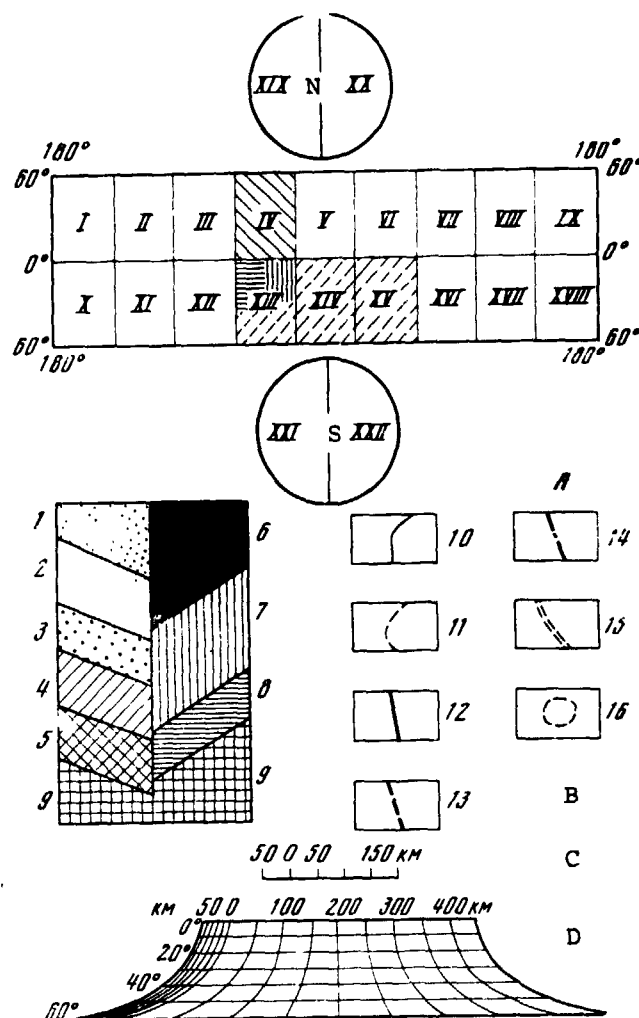


Fig. 2. The structural and geologic lunar chart (Sheets I-XXII).

A - A diagram showing the position of chart sheets. Sections of the chart are shown compiled according to information by M.S. Markov (vertical shading), A.L. Sukhanov (oblique intermittent shading), P.V. Florenskiy (oblique shading), and L.M. Shkerin (horizontal shading). The chart for the remaining territory was compiled by the author.

B - Symbols on the chart. Rock complexes outside of craters (1-4. mare, 5. partially mare): 1. youngest mare formations (M); 2. Procellarum (Pr); 3. Median (Md); 4. Altaic (Al); 5. Nebular (Nb).

Crater complexes of rocks (shown in their composition, according to information by A.L. Sukhanov, arranged outside of craters or positive accumulative formations alongside them): 6. Copernican (Cp) and Eratosthenian (Er); 7. Archimedian (Ar) and Ptolemaic (Pt);

Fig. 2 (cont.) 8. Hipparchian (Hp); 9. ancient crater (Php) and formations outside of craters (Ant), partially younger formations which have undergone intensive reworking and therefore are indistinguishable from old ones. The mutual arrangement of symbols indicates the age relationships between complexes. The characteristics of complexes 1-9 are shown in Table 1. The boundaries of rock complexes (in their clear structural and morphological expression): 10. reliable; 11. suggested (elements of the internal structure of craters are shown by the same symbol).

Fault disturbances: 12. reliable pre-Procellarum; 13. suggested pre-Procellarum; 14. post-Median.

Structural forms of the mare surface: 15. mare ridges; 16. mare domes

C - Scale for latitudes 60-90°

D - Scale for latitudes 0-60°

Roman numerals on the chart.

Mare basins:

I-XXXIII - see Table 2	XLV - Mare Marginis
XXXIV - Sinus Iridum	XLVI - Mare Veris
XXXV - Oceanus Procellarum	XLVII - Mare Autumni
XXXVI - Mare Nubium	XLVIII - Mare Pacis
XXXVII - Mare Tranquillitatis	XLIX - Mare Struve
XXXVIII - Mare Fecunditatis	L - Sinus Roris
XXXIX - Mare Australe	LI - Sinus Aestuum
XL - Mare Frigoris	LII - Sinus Medii
XLI - Mare Vaporum	LIII - Lacus Somniorum
XLII - Mare Anguis	LIV - Palus Putredinis
XLIII - Mare Undarum	LV - Palus Epidemiarum
XLIV - Mare Spumans	

Arabic numbers on the chart.

Mountains:

1. Altai	8. Pico
2. Alps	9. Pyrenees
3. Apennines	10. Straight
4. Haemus	11. Rocky
5. D'Alembert	12. Teneriffe
6. Caucasus	13. Jura
7. Cordillera	14. Agarum Promontory

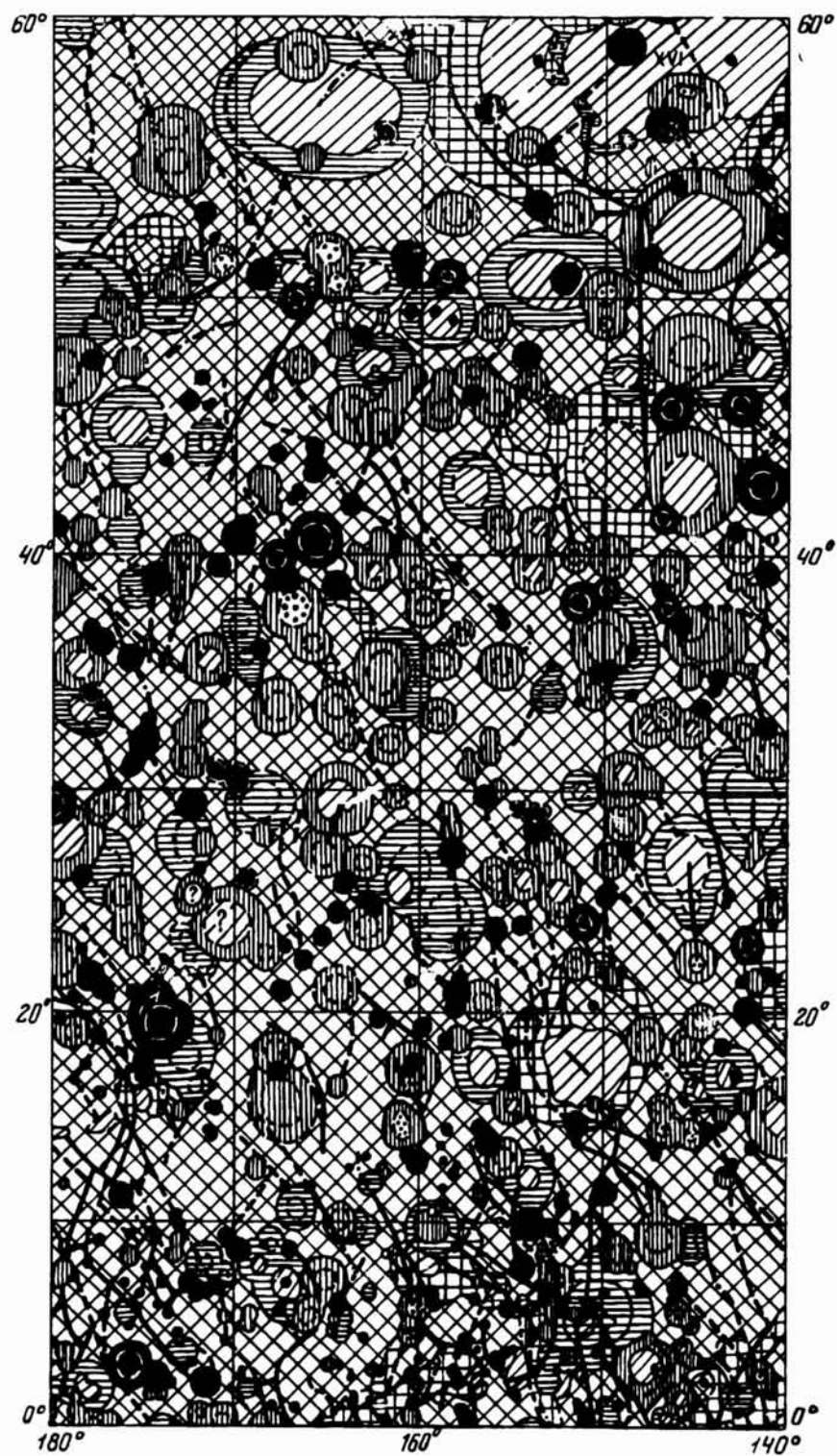
Fault systems:

15. Alpine Valley	18. Cauchy Fault
16. Apollonius I Fault	19. Rheita Valley
17. Ariadaeus Fault	20. Sulpicius Gallus Fault

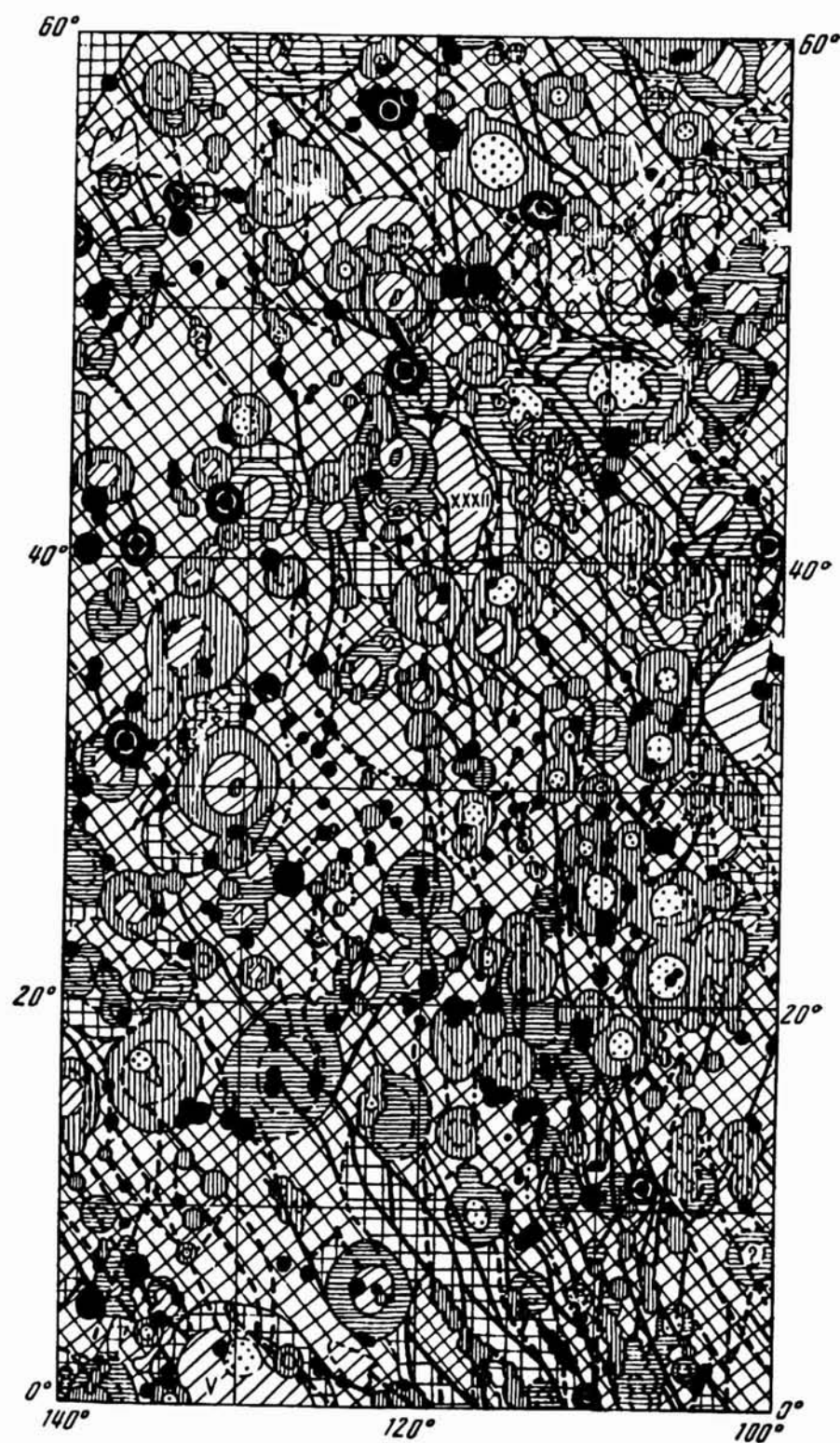
Craters:

- | | |
|-------------------|--------------------|
| 21. Autolycus | 70. Regiomontanus |
| 22. Alexander | 71. Riccioli |
| 23. Apollonius B | 72. Y. Ross |
| 24. Aratus | 73. Rothmann G |
| 25. Aristarchus | 74. Sacrobosco |
| 26. Aristillus | 75. Taruntius |
| 27. Archimedes | 76. Tacquet |
| 28. Belkovich | 77. Theophilus |
| 29. Biot B | 78. Timocharis |
| 30. Beaumont | 79. Tycho |
| 31. Boussingault | 80. Torricelli |
| 32. Walter | 81. Ukert |
| 33. Geminus | 82. Wallace |
| 34. Hyginus | 83. Firmicus |
| 35. Glaisher W | 84. Fracastorius B |
| 36. Gaudibert | 85. Fracastorius G |
| 37. Goclenius | 86. Hahn |
| 38. Grimaldi | 87. Julius Caesar |
| 39. Humboldt | 88. Censorinus C |
| 40. Gutenberg G | 89. Tsiolkovsky |
| 41. Daguerre | 90. Shaler |
| 42. Delisle | 91. Schickard |
| 43. Dionysius | 92. Jansen |
| 44. Isidorus | 93. Delambre |
| 45. Capella | 94. Jansenn |
| 46. Cassini | |
| 47. Catharina | |
| 48. Kästner | |
| 49. Clavius | |
| 50. Clausius | |
| 51. Cleomedes | |
| 52. Colombo | |
| 53. Condorcet | |
| 54. Copernicus | |
| 55. Xenophanes | |
| 56. Lambert | |
| 57. Langrenus | |
| 58. Le Monnier | |
| 59. Letronne | |
| 60. Manilius | |
| 61. Menelaus | |
| 62. Mersenius | |
| 63. Nansen | |
| 64. Petavius | |
| 65. Piccolomini G | |
| 66. Pytheas | |
| 67. Plato | |
| 68. Polybius | |
| 69. Purbach | |

/190

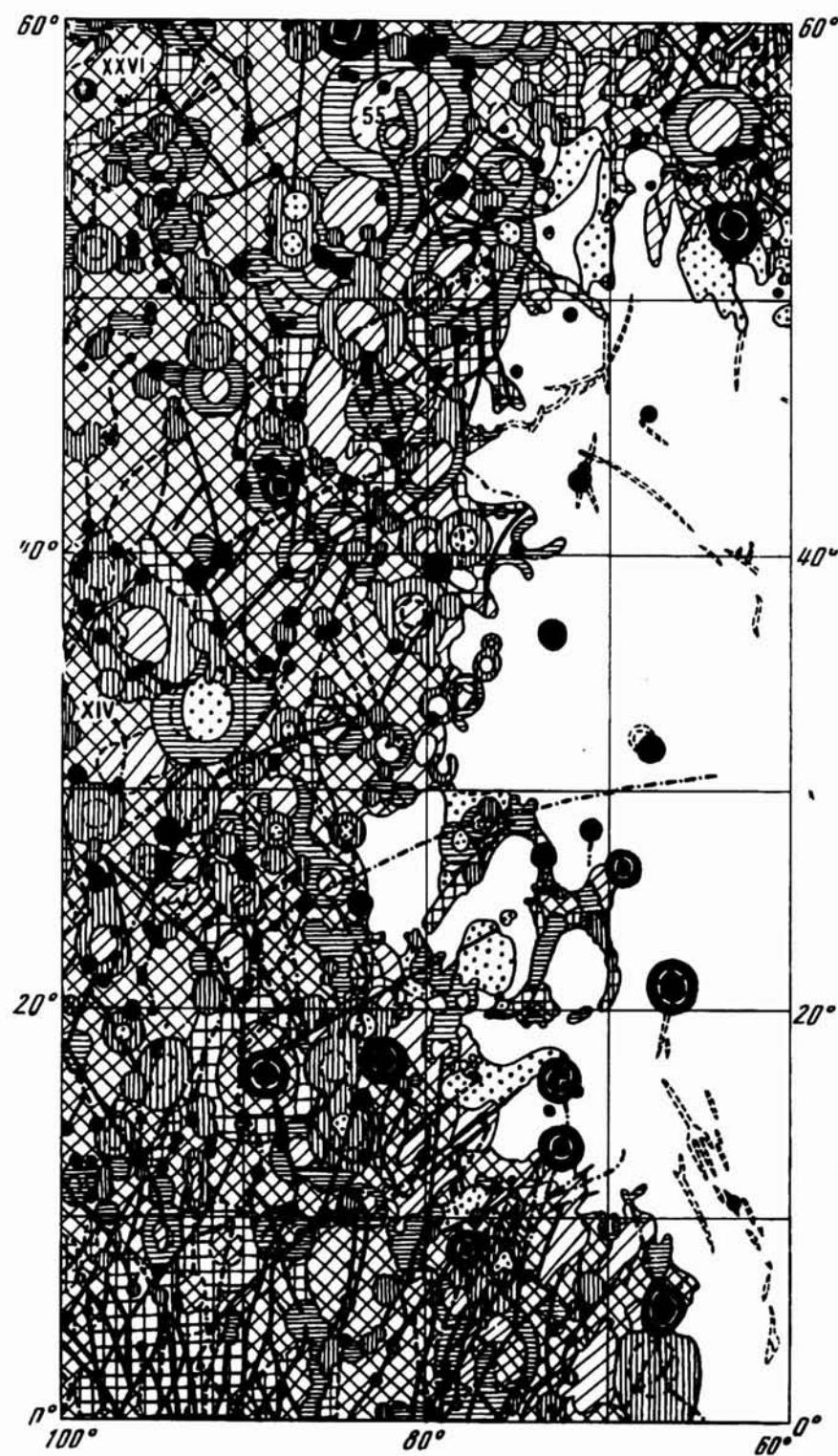


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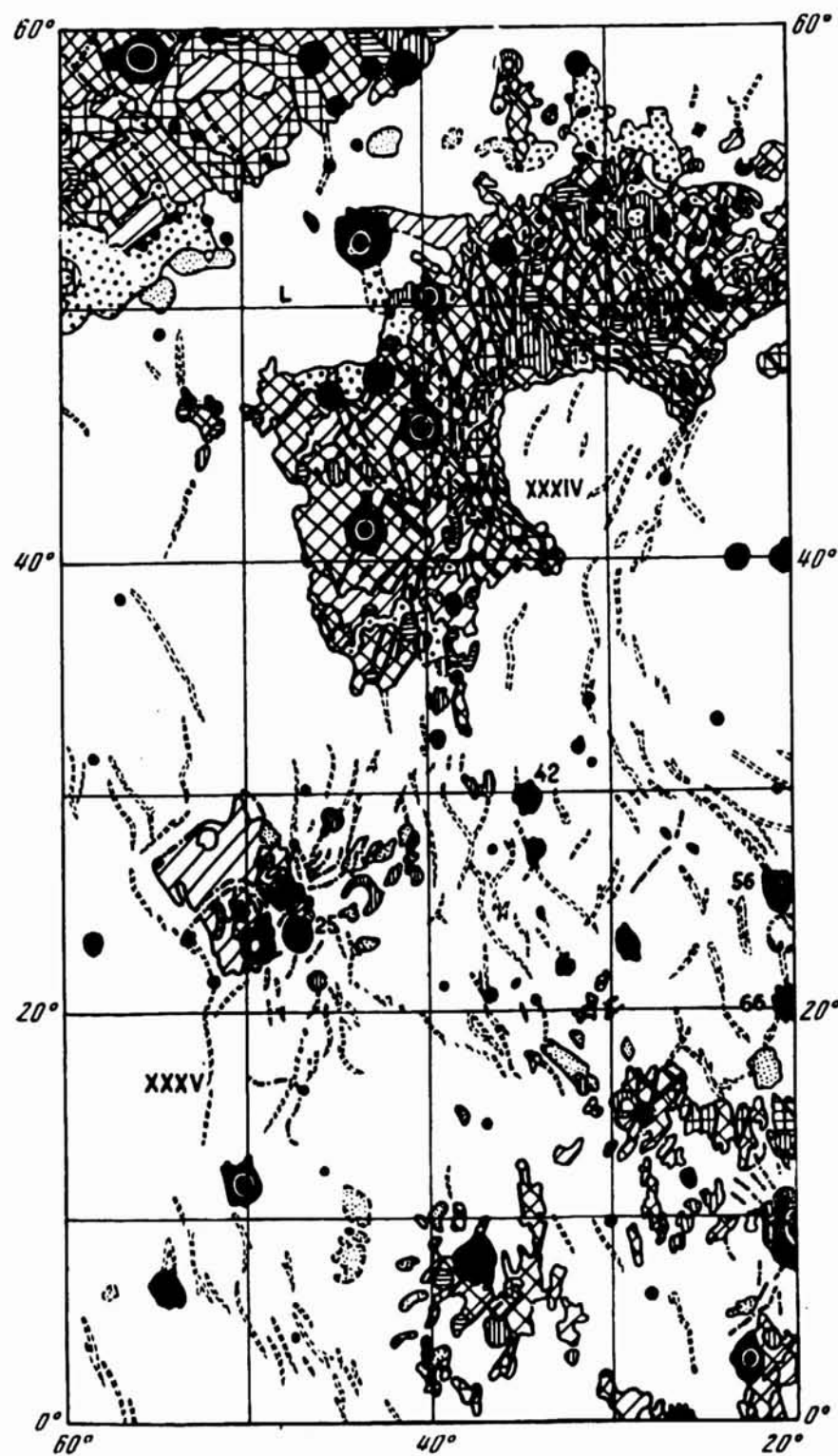


/191

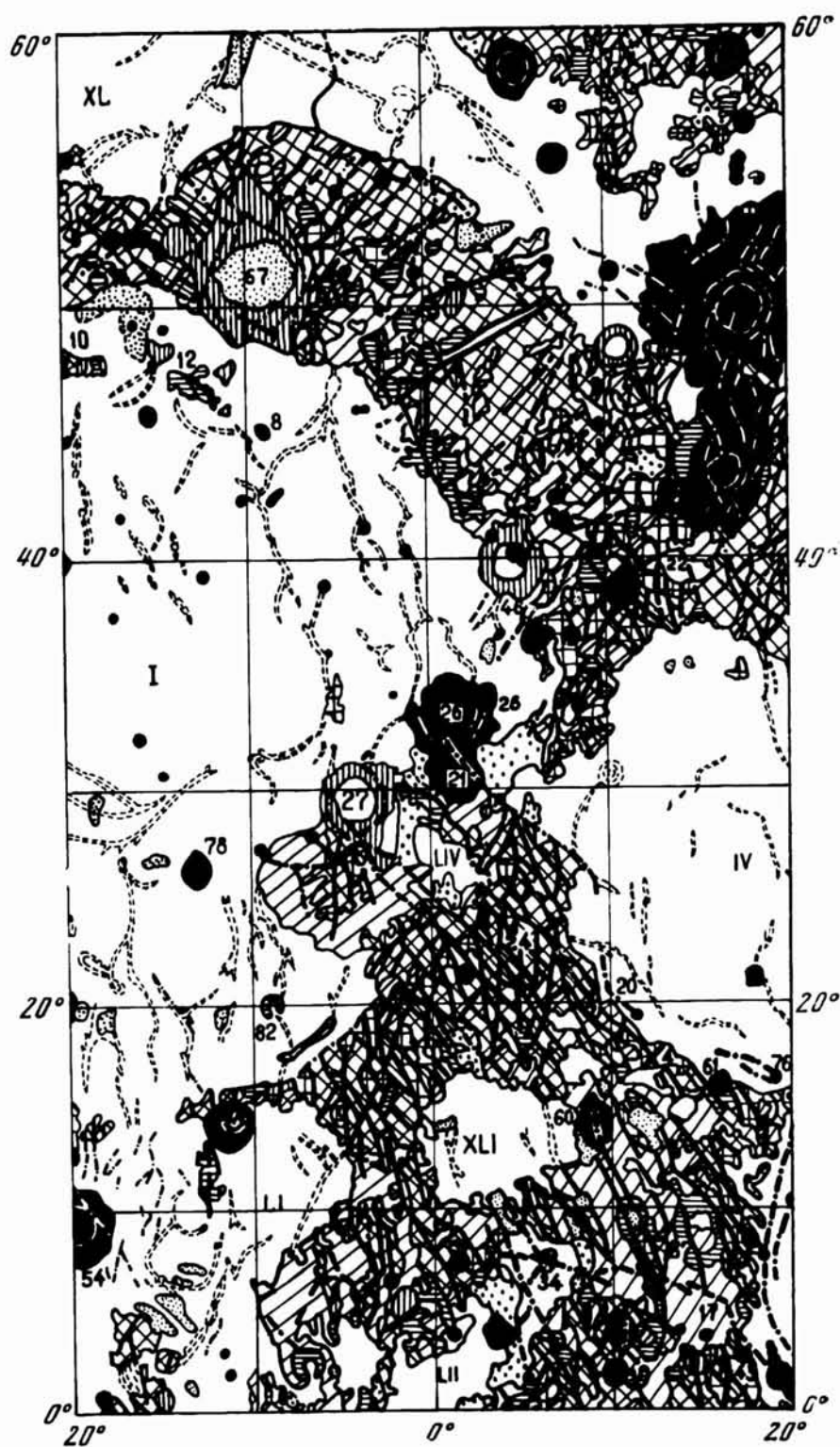
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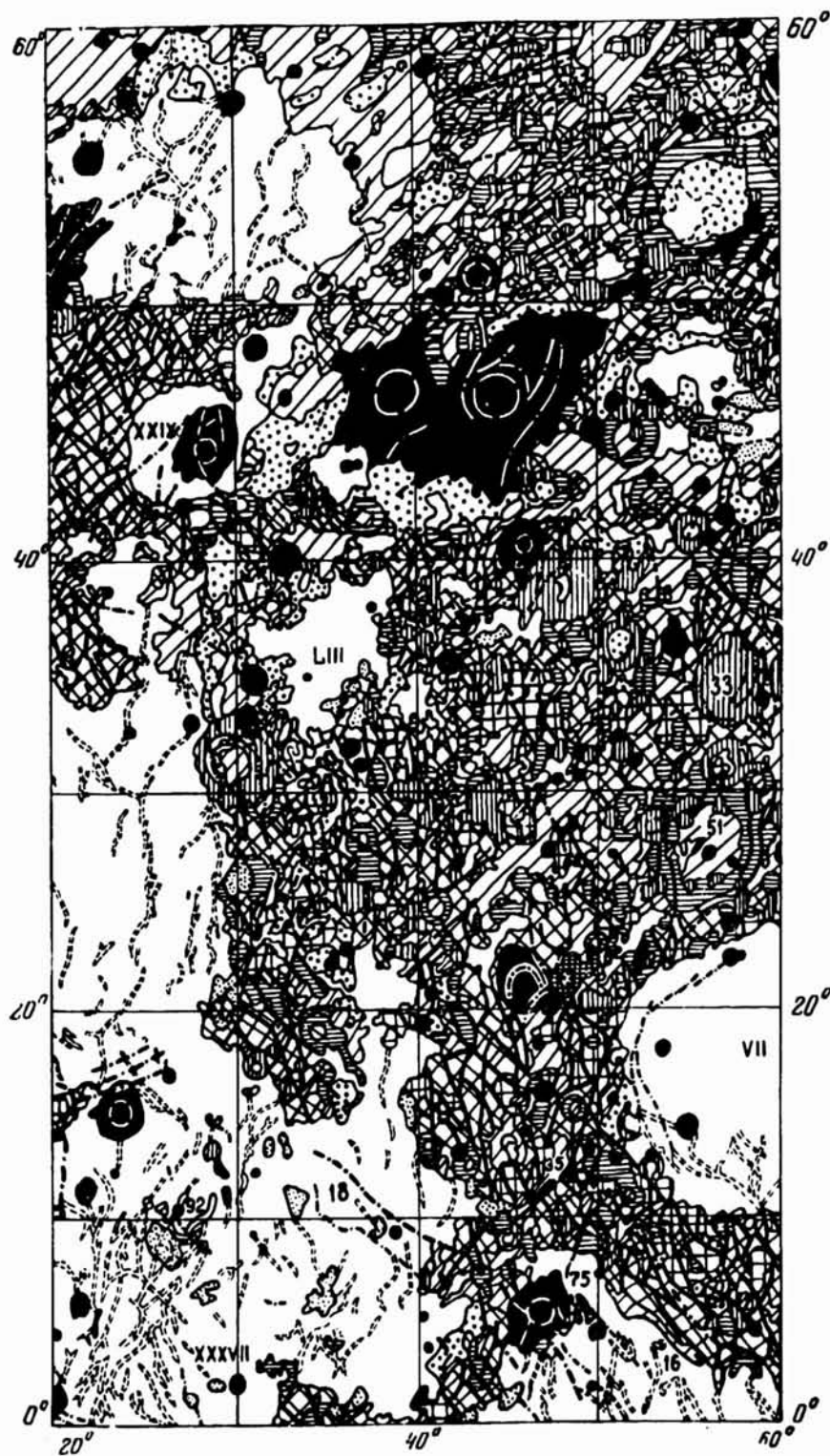


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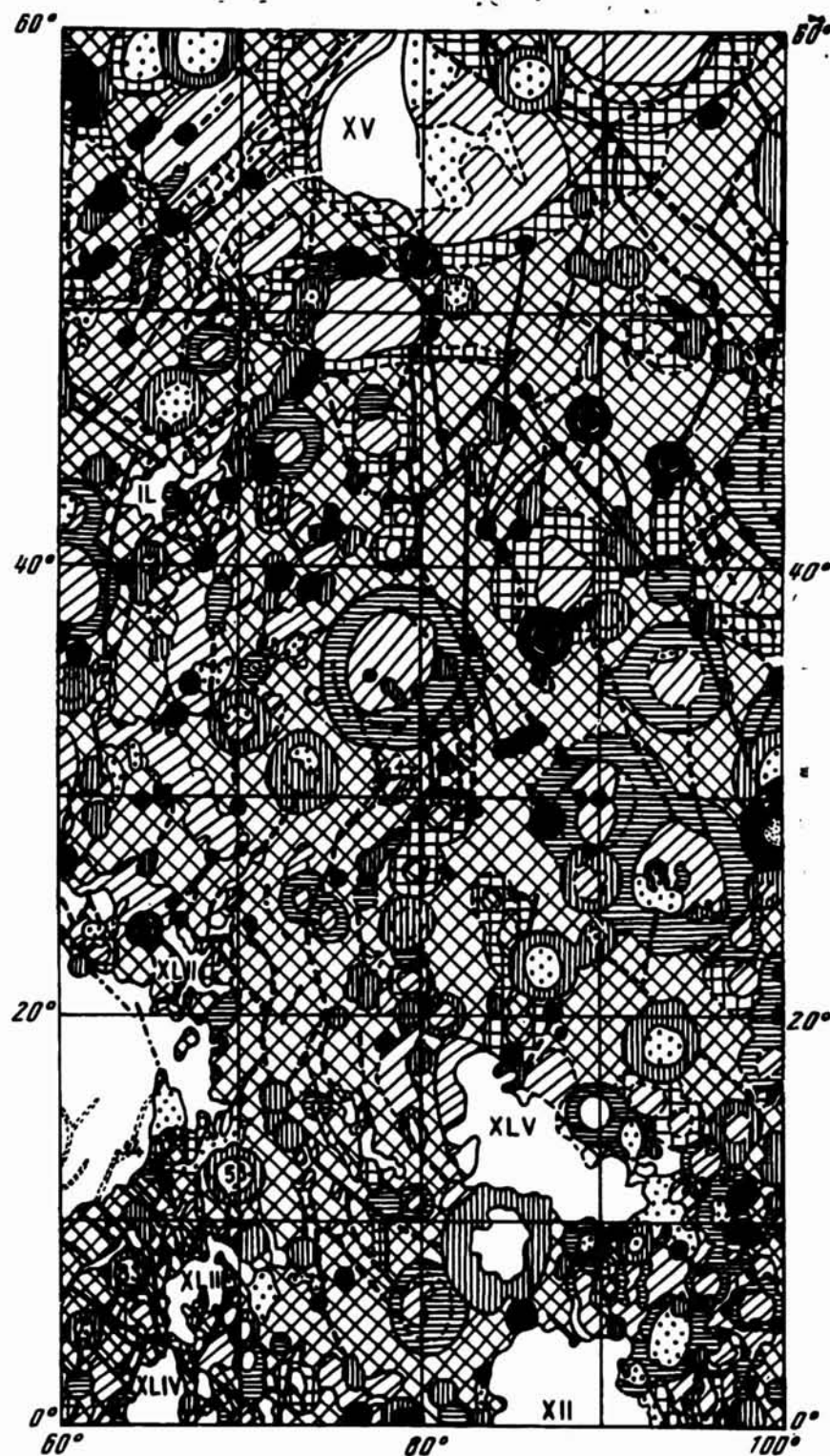


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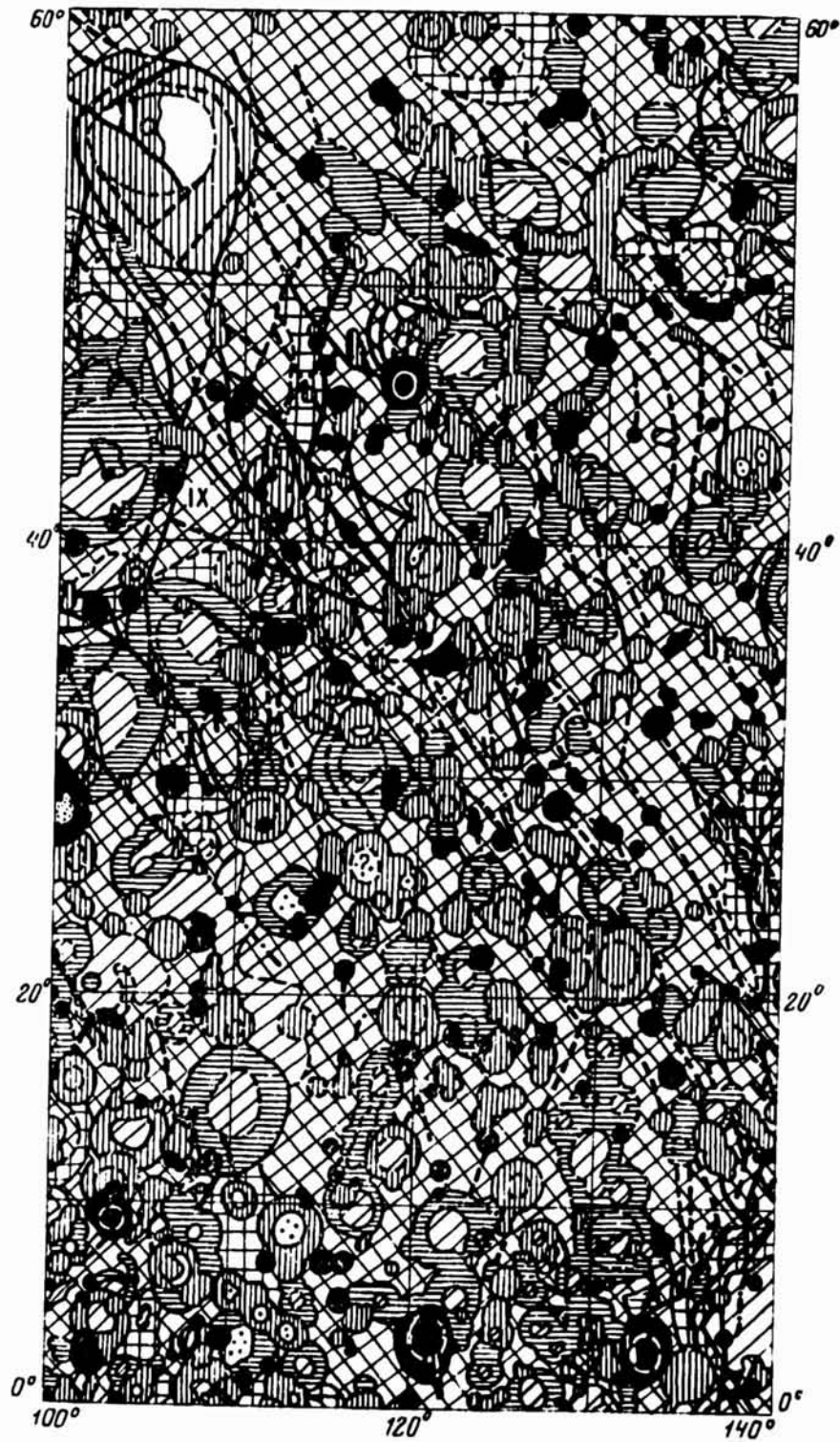




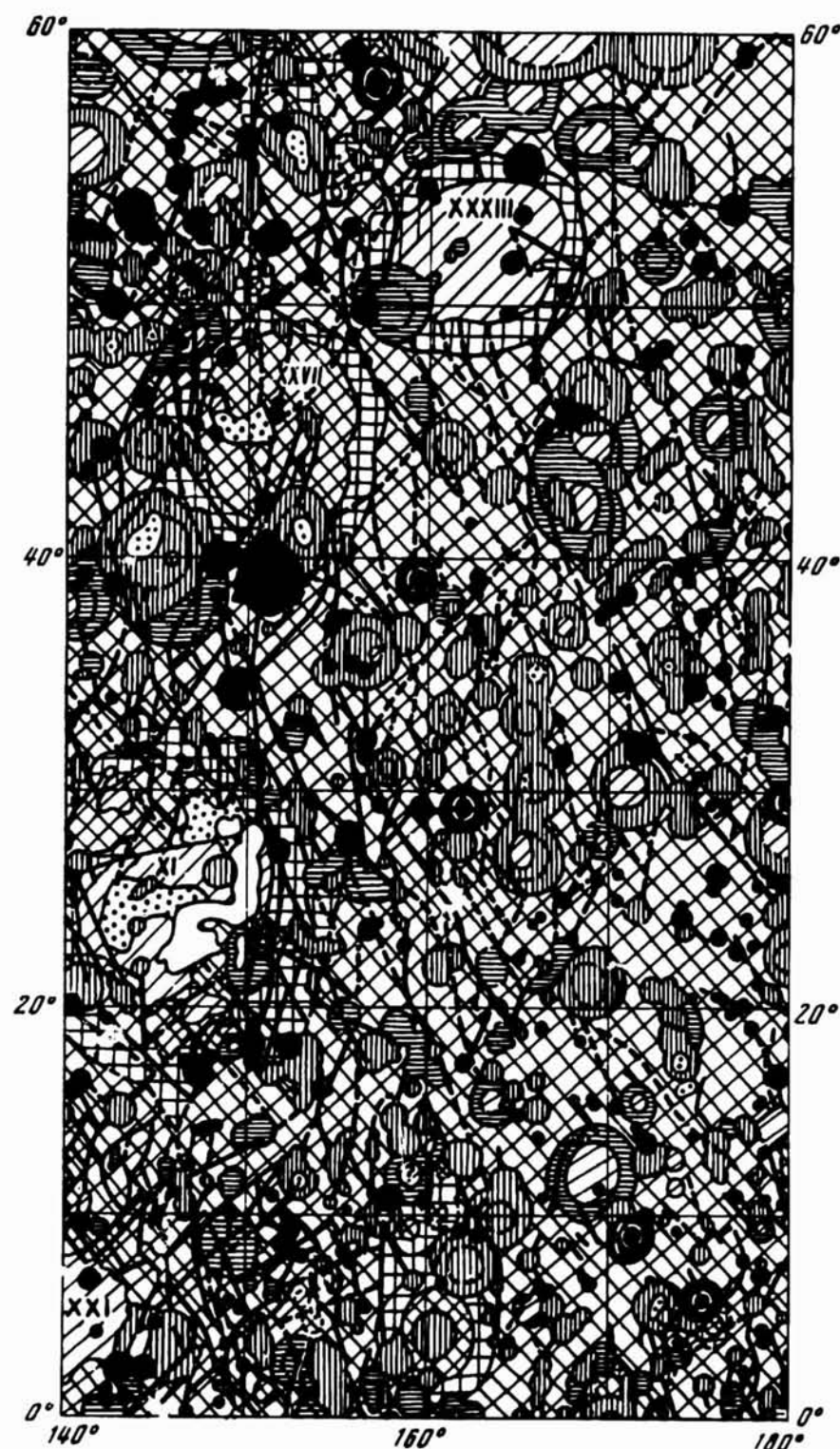
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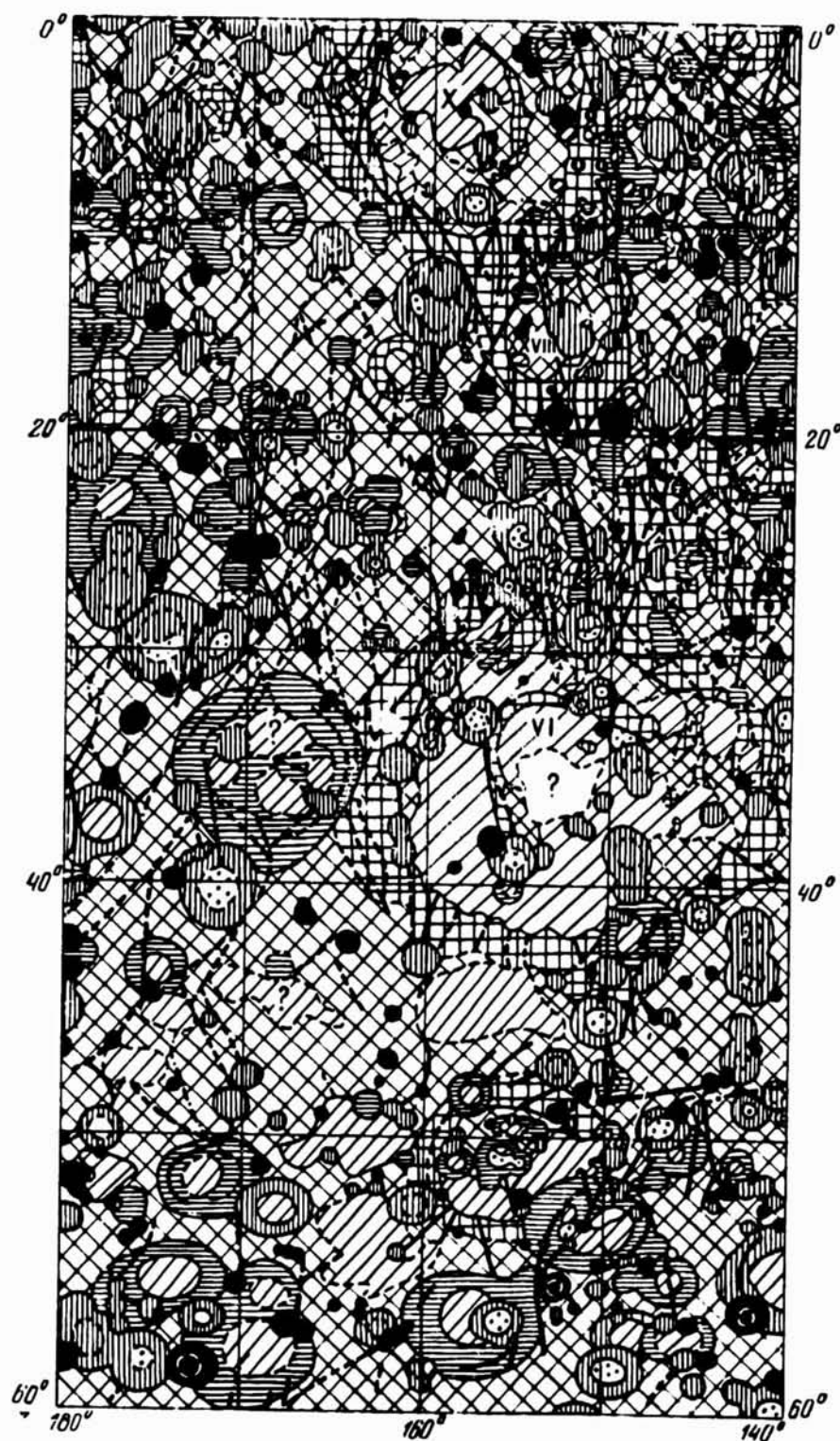
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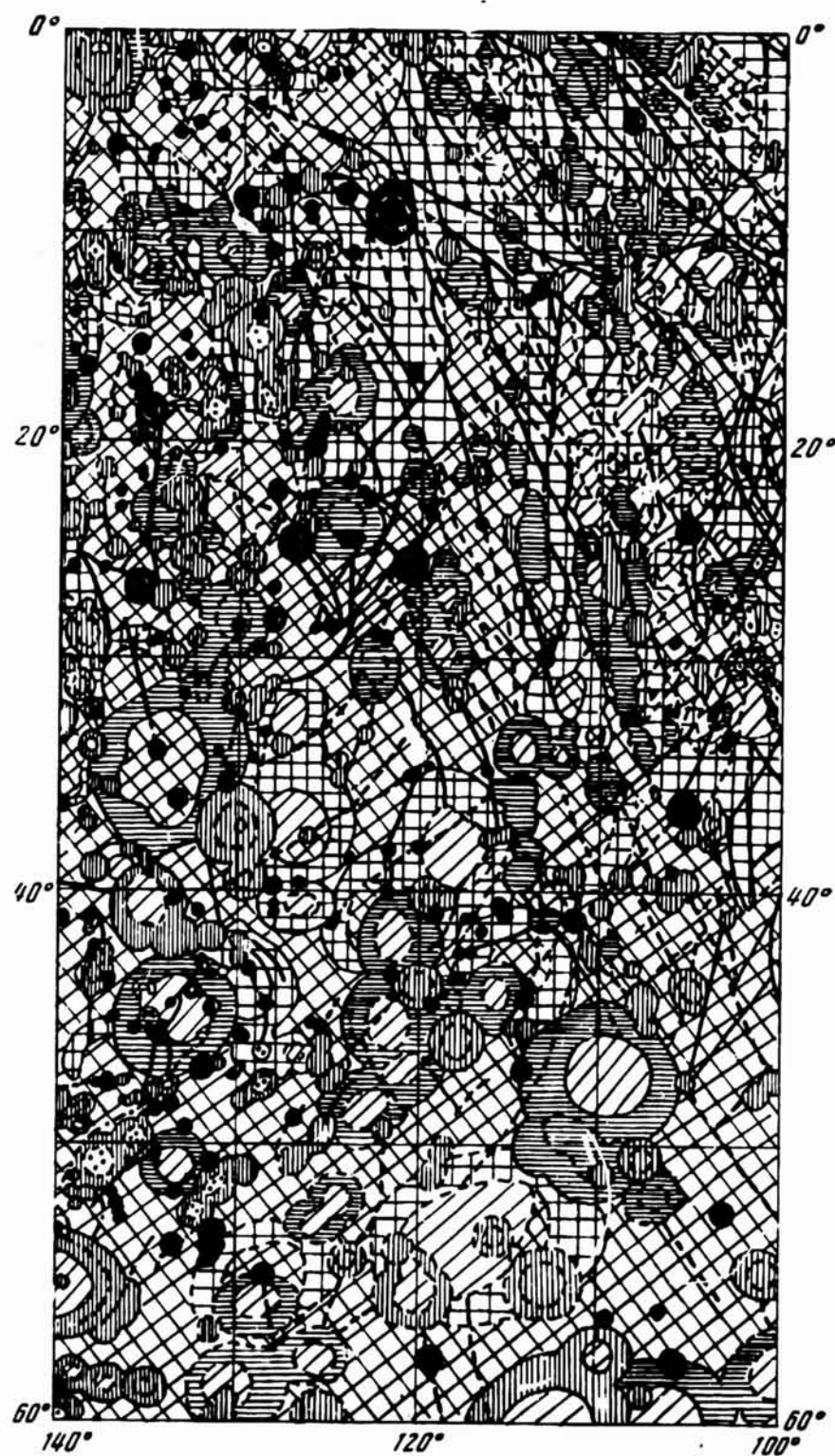
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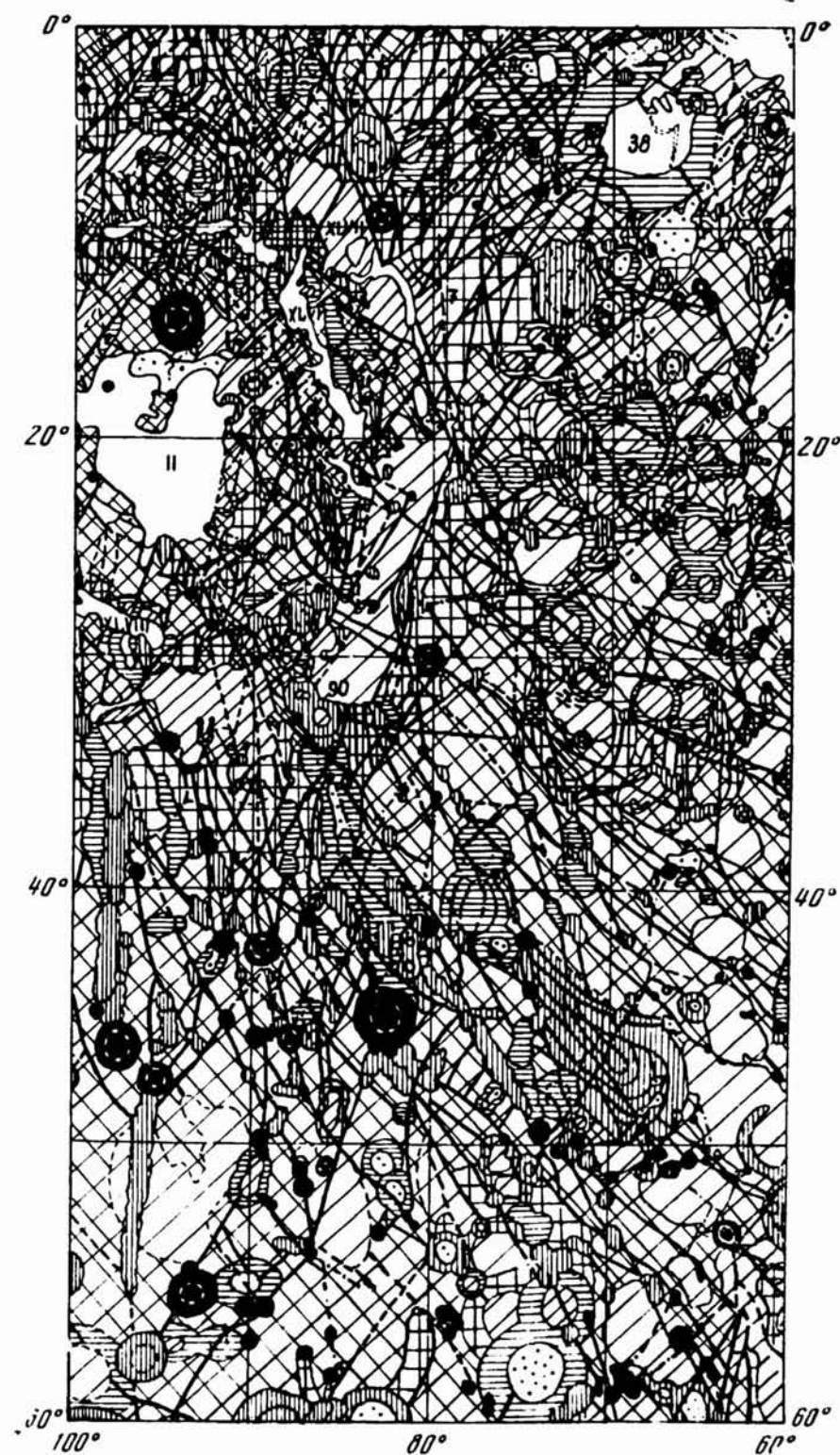
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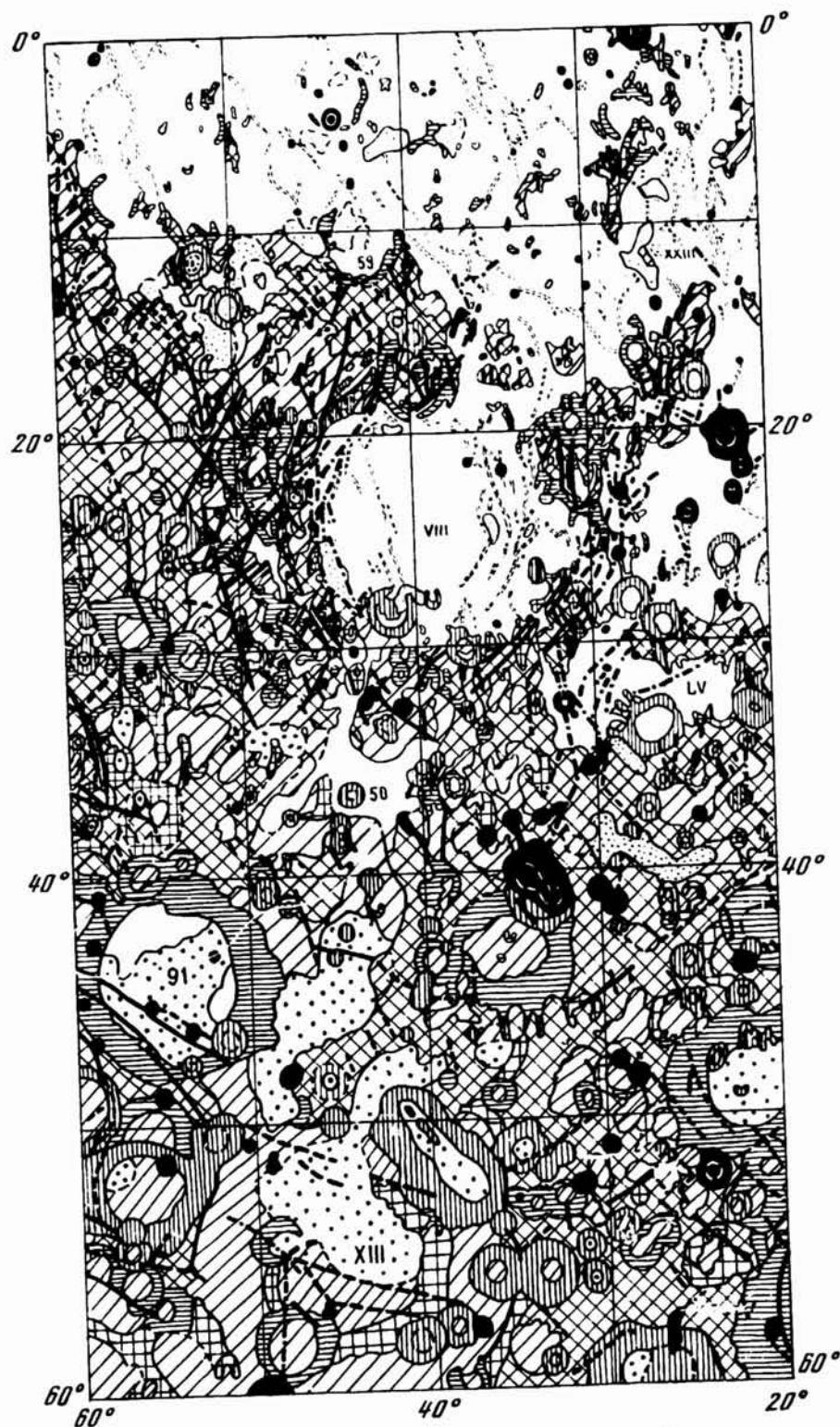
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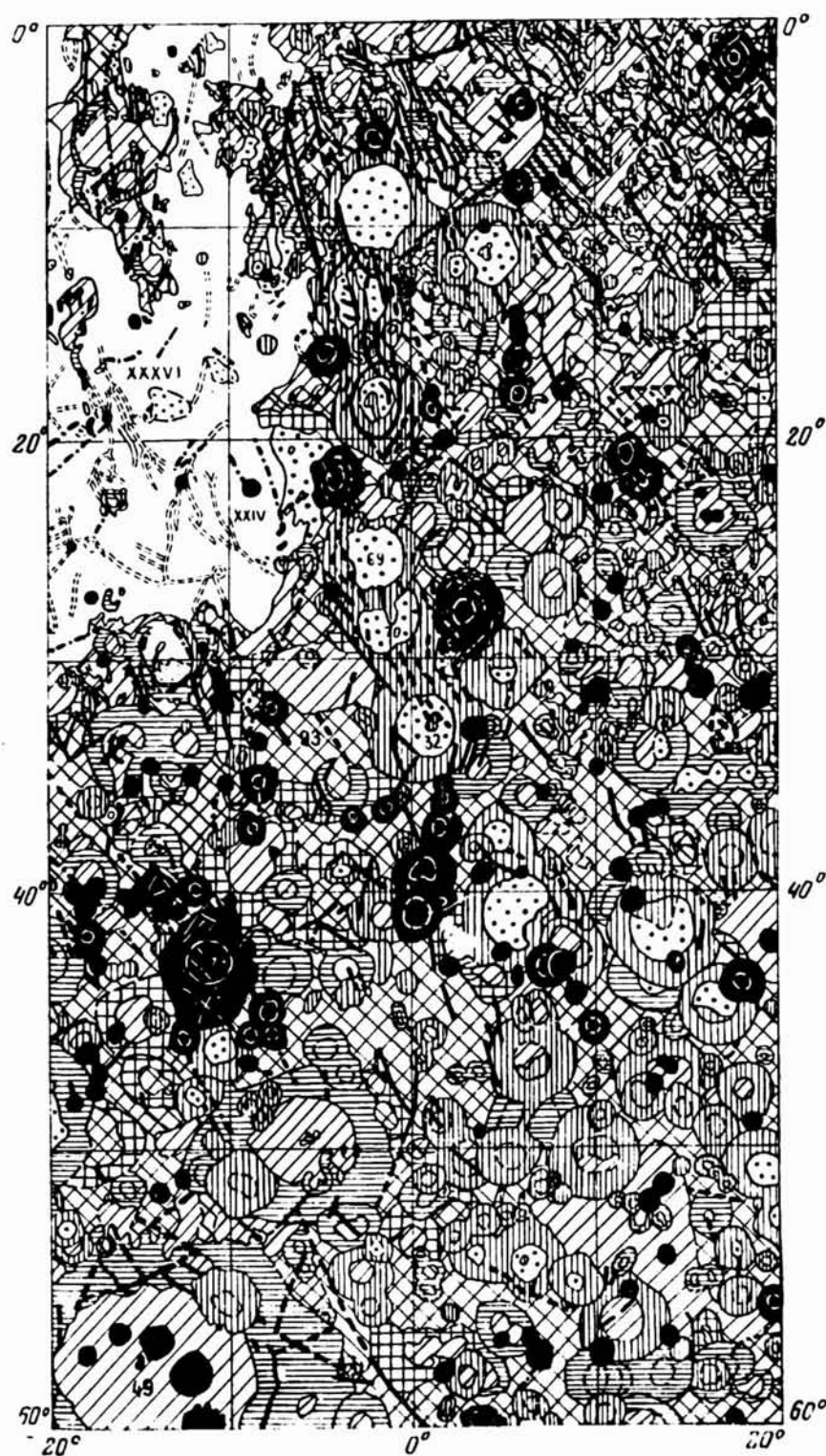
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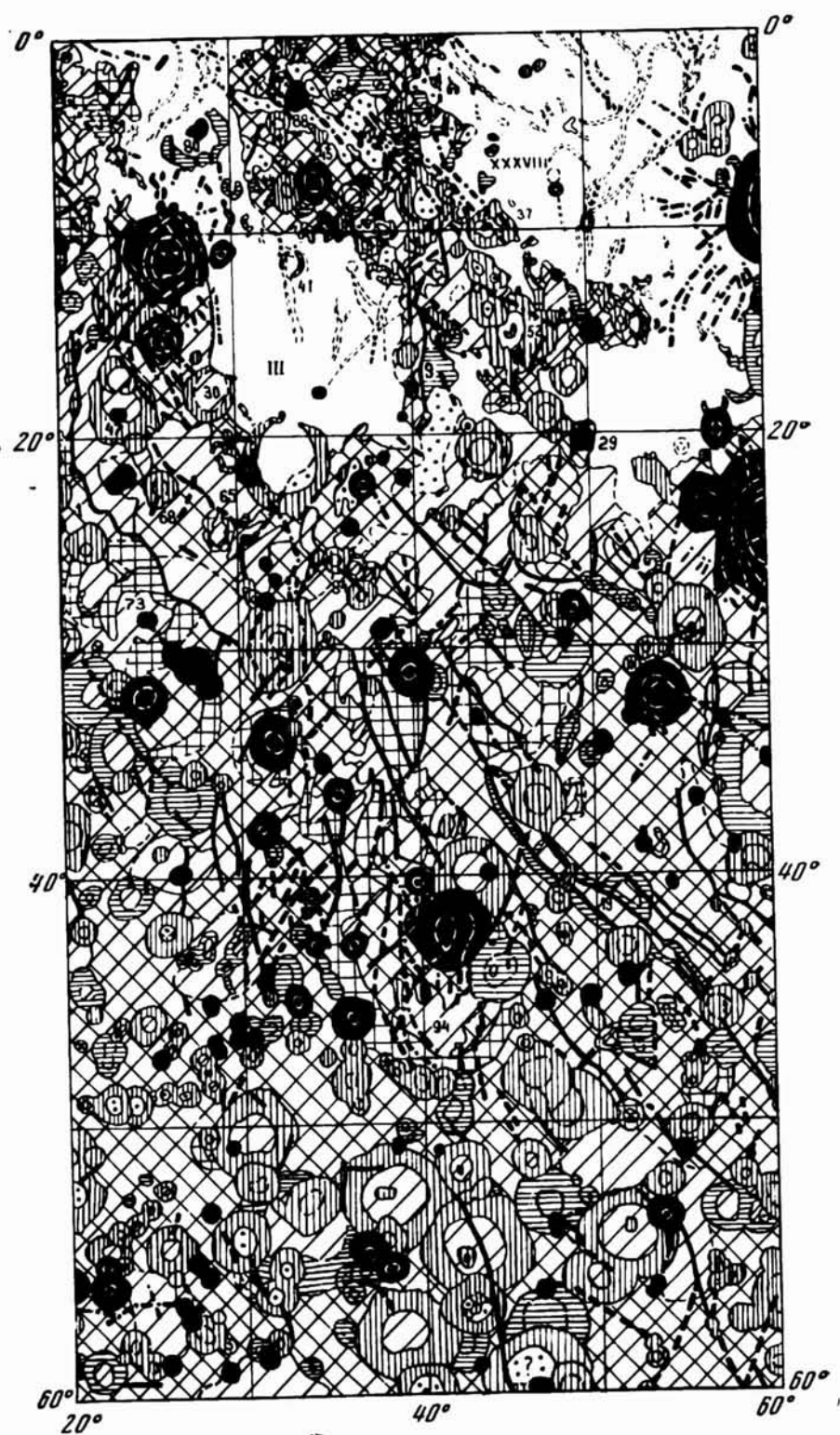
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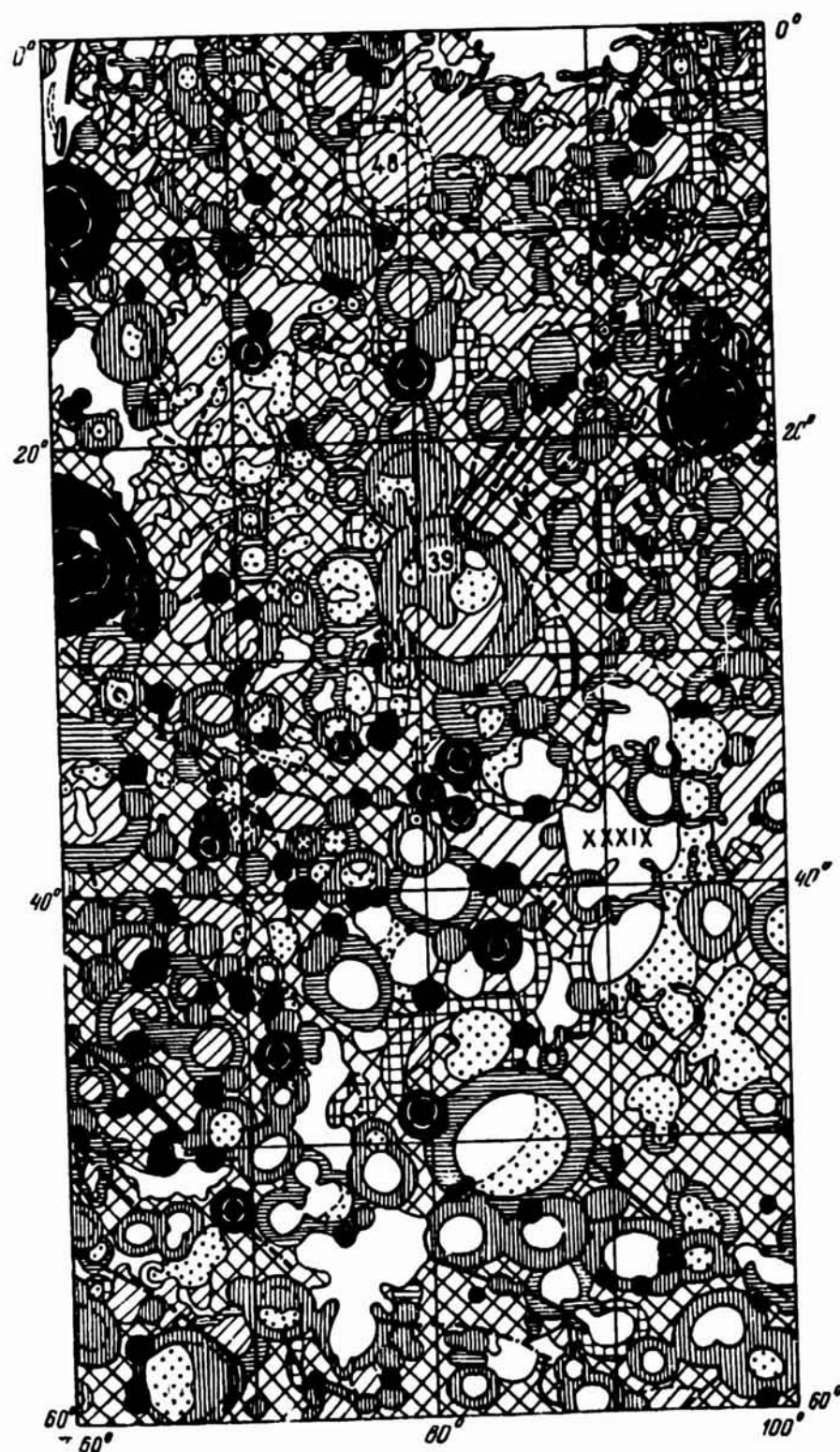
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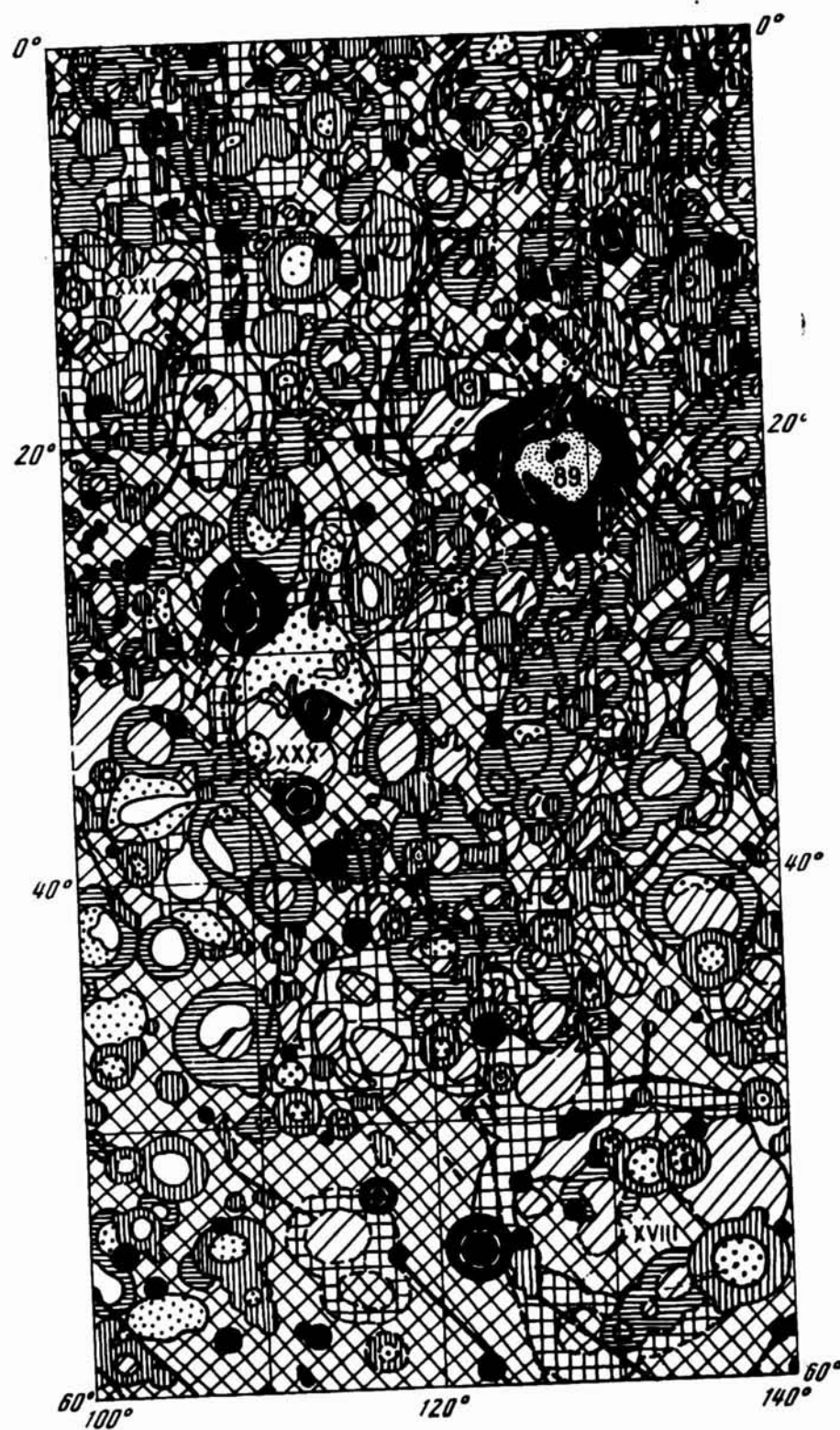
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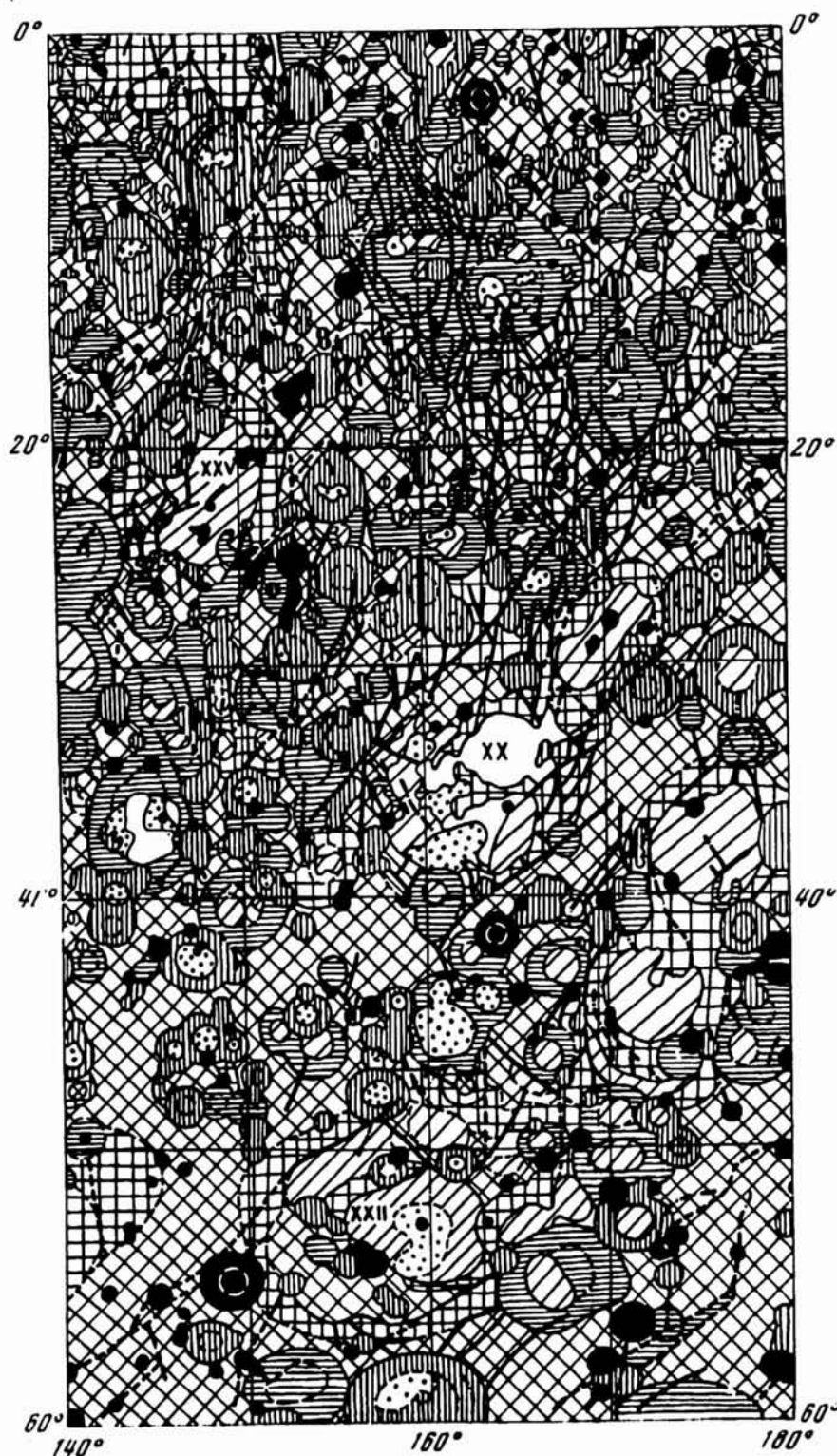
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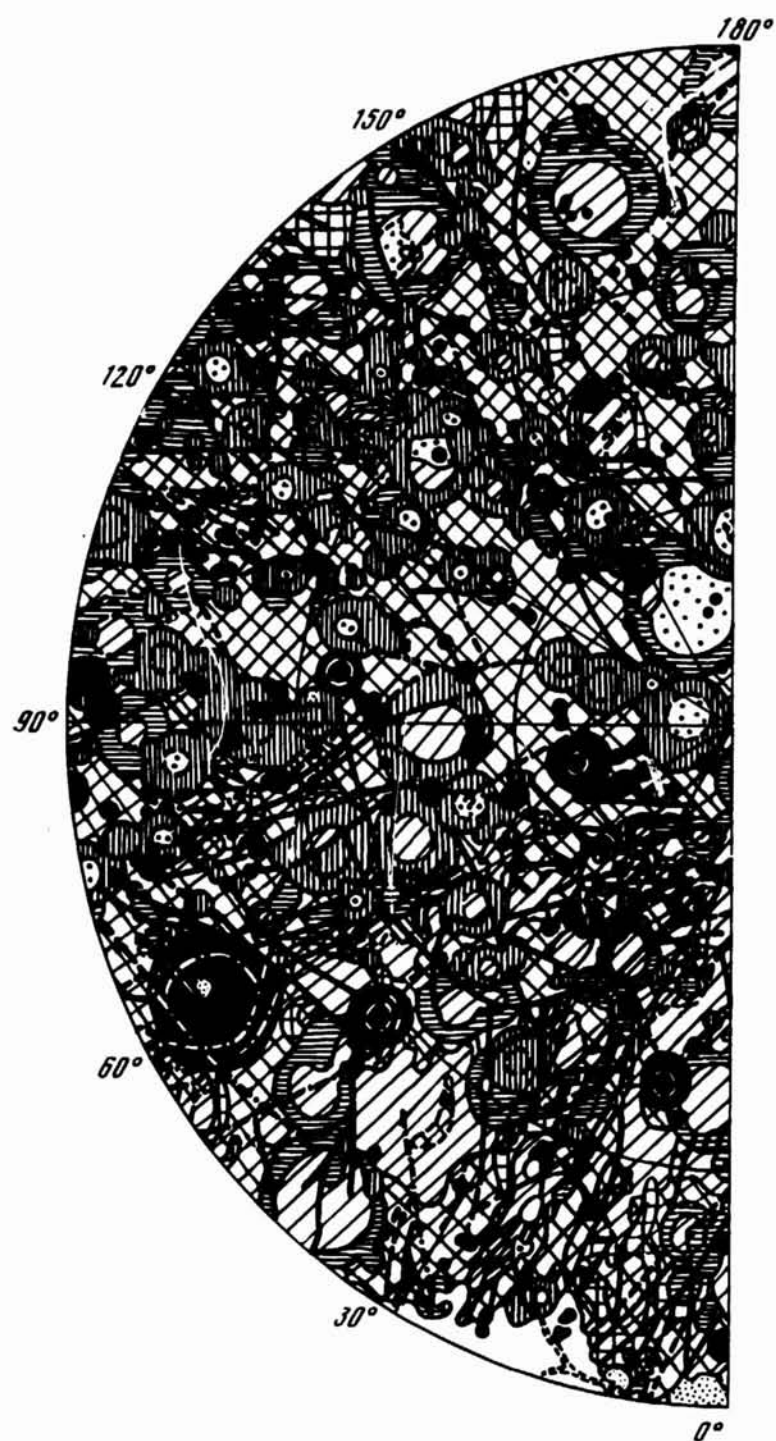
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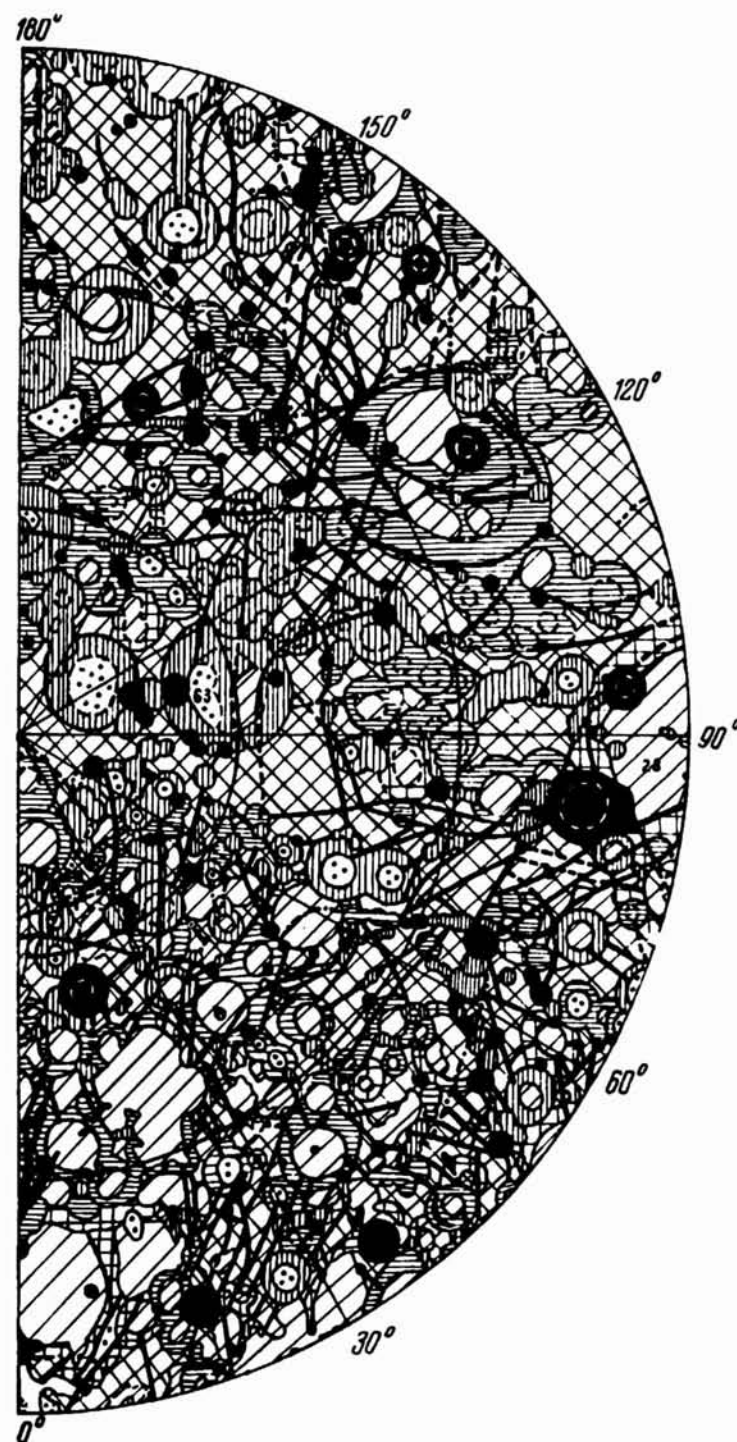
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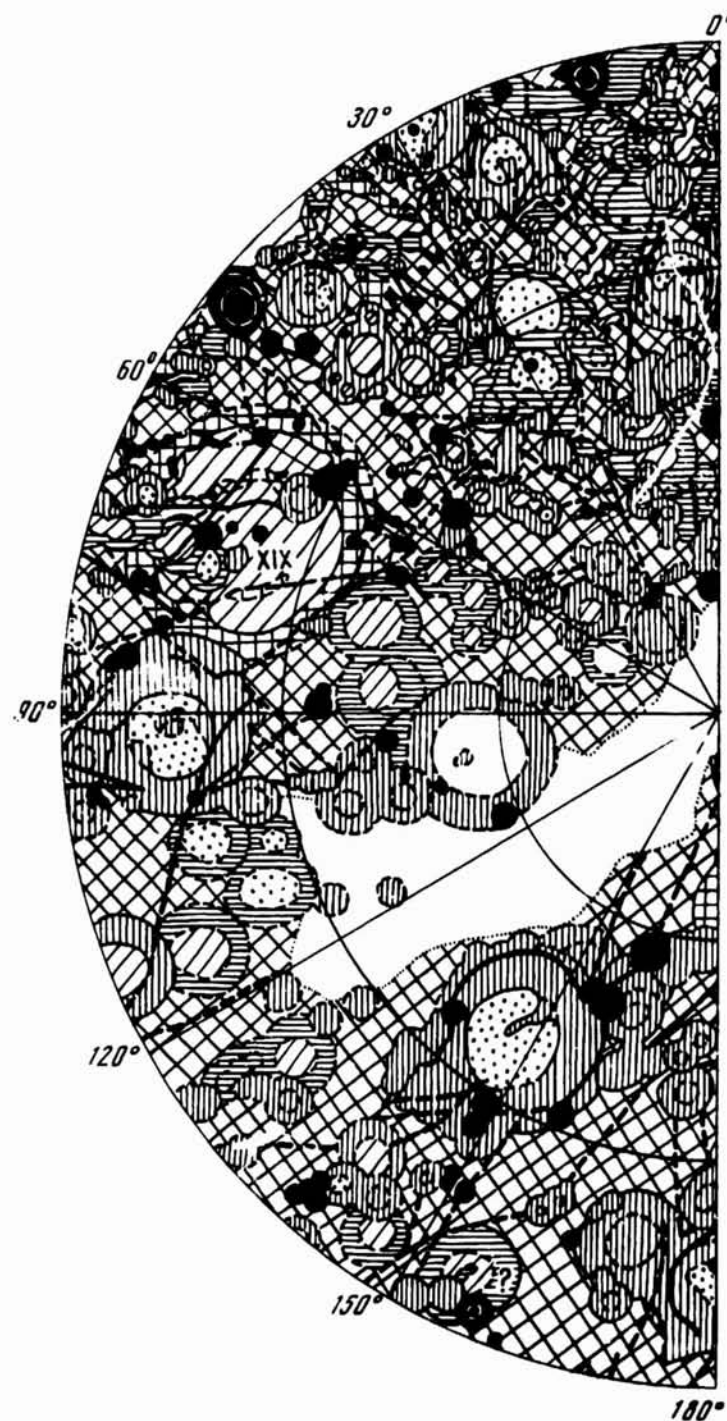
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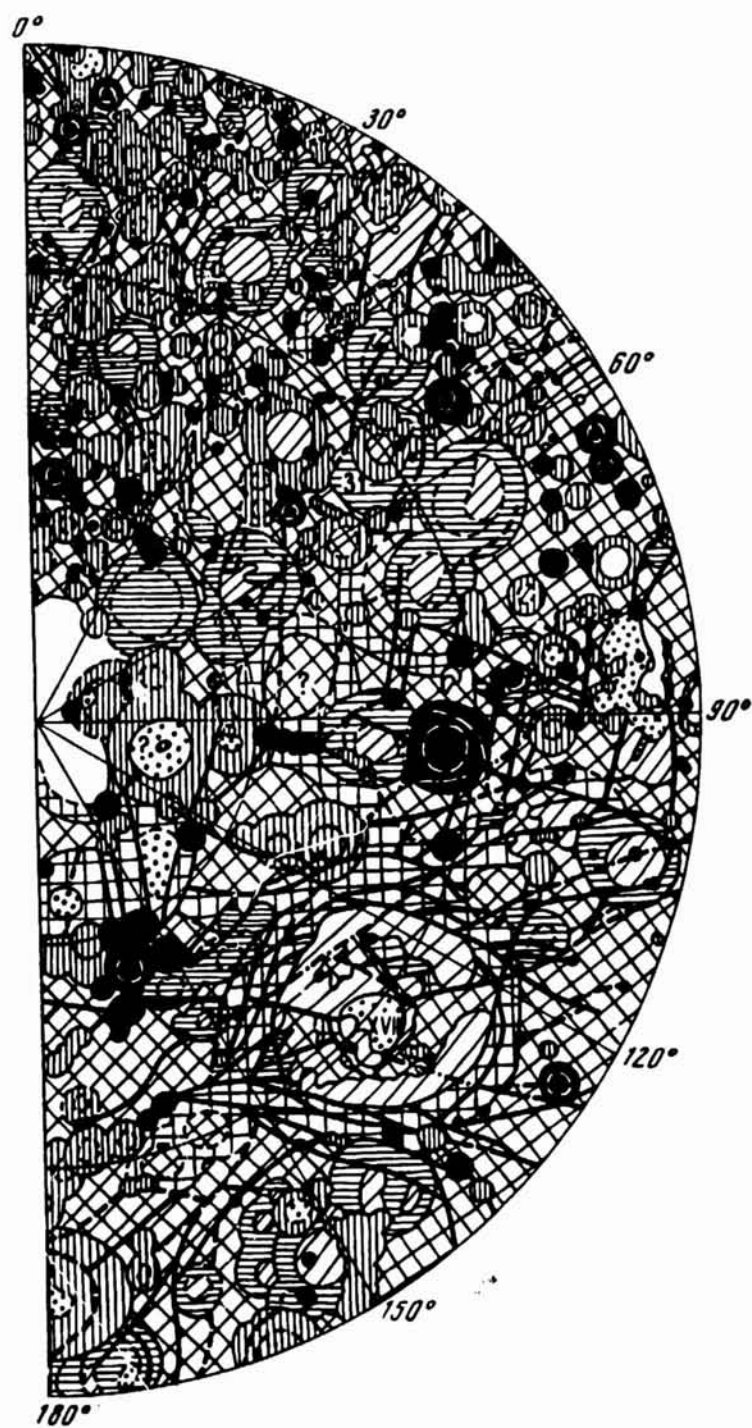
Sheet XIX



Sheet XX



Sheet XXI



Sheet XXII

The work was carried out in the study of comparative planetology of the Institute of Geology of the USSR Academy of Sciences, under the direction of M.S. Markov, to whom the author gives his sincere thanks. The author expresses his gratitude to Academician A. B. Peyve, A. L. Sukhanov, K. P. Florenskiy, P. V. Florenskiy, A. V. Khabakov, and N. A. Shtreys for their consultations and observations while the material was being prepared.

The Multistage Nature of Formation Processes of Lunar Mare Basins

Circular Basins of the Mare Imbrium Type

Mare Imbrium (I, see Fig. 2, sheets IV, V) has been studied more than other mare basins, and can be looked upon as a standard for structures of a similar type because of the reliably expressed features of its geologic development. Therefore, it will be described in particular detail.

Mare Imbrium is an oval basin, in the first approximation, with diameters of 1100 and 1200 km, complicated by the semi-oval Sinus Iridum. External and internal zones can be seen in it. In the northwest, the boundary of the latter coincides with the boundary of the mare, and to the southeast is marked by exposures of an old base, younger mountainous peaks and a system of large craters in the south. The boundary of the internal zone can be traced from the Straight Range, Teneriffe and Pico to Spitzbergen and the western edge of the Archimedes cirque, and afterwards is joined to the highland region of the northwest edge of the mare via the craters Timocharis, Lambert and Delisle.

The boundaries of Mare Imbrium are characterized by aligned sections joined at an angle to each other, such as the southwest slope of the Alps and the northwest slopes of the Apennine system -- the southern part of the Caucasus and on sections of the northwest strike of the boundary of Sinus Iridum. Similar sections can also be seen in the system of mare ridges of the internal slope of the Mare (see Fig. 2). Strikes of rectilinear marginal sections and mare ridges coincide with the most extensive fault directions on the boundary of the Mare. /188

The surfaces of the internal and a considerable part of the external zones of Mare Imbrium are made up of rocks of the Procellarum complex. Over a very large part of the mare surface they have a relatively high (within the characteristics of this complex) albedo. As a rule, darker sections gravitate towards the edges of the Mare. One of these takes in the western half of Sinus Iridum and can be traced to the south as far as Delisle. There are others in the regions of Timocharis, Palus Putredinis, and east and north of the crater Wallace. One of the darkest

sections, on which Copernican crater rays west of the Plato cirque are interrupted, is north of the Straight Range near the edge of the mare. Probably, this section is composed of post-Procellarum mare formations. It can be assumed that other dark sections are also younger than the lighter ones. Older mare formations of Median and Altaic complexes occur on the surface in the external zone of the eastern part of the Mare. They cover comparatively small areas. /212

There are also many exposures of rocks of the Procellarum complex differing noticeably in brightness within the peripheral belt of the basin. Hence, Mare Vaporum and the central part of Mare Frigoris, as a whole, are darker than Sinus Aestuum and Sinus Medii and the eastern part of Oceanus Procellarum. There are particularly dark patches between Sinus Aestuum and Sinus Medii, in the north of Sinus Medii, in the eastern part of Mare Vaporum, between them and Mare Claritas and on the floor of the Plato cirque. In the vicinity of Manilius, Hyginus and Mare Frigoris, northeast of Plato, the dark formations interrupt the rays of Copernican craters, which gives basis to relate them to the complex of the youngest mare rocks. In Sinus Medii, Mare Frigoris and Sinus Roris, there is a Median complex. Altaic formations make up a considerable area between Sinus Aestuum and Sinus Medii, and there are individual patches of them in other parts of the belt (see Fig. 2).

The different ages of mare formations of the Mare Imbrium basin and basins in the peripheral belt indicate the multistage process in which these structural forms were filled with mare material, but it is still not known whether these basins developed while they were being filled or were formed earlier. We shall examine the features of the elevation position of surfaces of complexes outside of craters to answer this question. /213

Detailed mapping of the central part of the visible hemisphere and a review of the remaining territory for which individual heights had been made showed that exposures of complexes outside of craters are level surface. On the boundaries of complexes, a more or less sharp scarp is seen on the side of a relatively young complex, that is, the latter is situated hypsometrically lower (Fig. 3). As they move away from circular mare basins and inside them (Fig. 4), on adjoining sections these level surfaces are parallel to each other and the surface of the Moon's figure (see profile for the geological and morphological chart in the book Problemy geologii Luny [Problems of Geology of the Moon], 1969). Apparently, this was the initial position of complex surfaces in the majority of regions on the Moon. However, they undergo characteristic warping on the boundaries of round basins and on marginal cordilleras; these have been studied best on the southeast edge of Mare Imbrium (Fig. 5). The surface complexes outside of craters gradually bulge as they approach the



Fig. 3. The region near the crater Hyginus (wide angle photograph 95; Orbiter 5). South of the crater there is a scarcely discernible scarp on the boundary of a Procellarum complex and a darker complex of most recent mare formations. The scarp is facing the side of the latter.

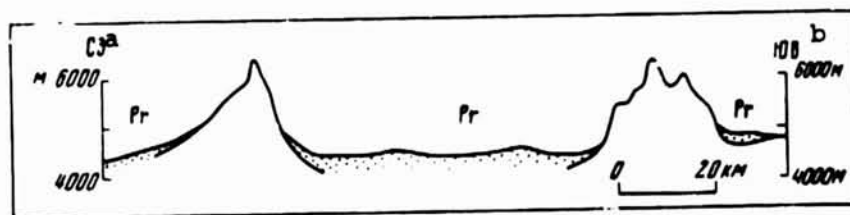


Fig. 4. A profile of the Moon's surface in the region of the Archimedes crater. The hypsometric level of the surface is similar to the Procellarum (Pr) rock complex (shown by dots) inside and outside the crater. Individual heights are taken from the LAC-41 chart ("Lunar chart," 1960-1964).

Key: a. Northwest
b. Southeast

Apennine range from the southeast, and then sharply fall away to the mare basin along marginal scarps. The older the complex outside the crater, the greater is the range of warping. Differences in warping ranges show that the bulging of a cordillera

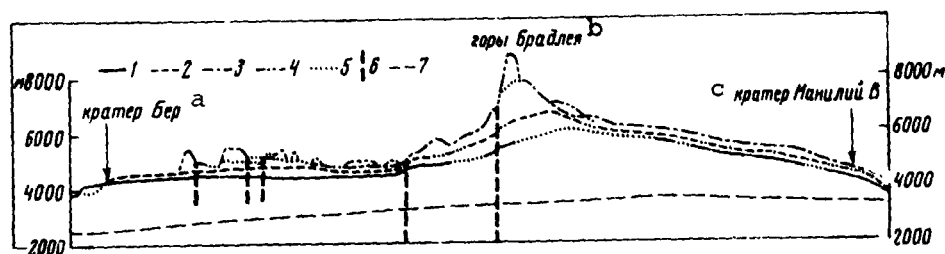


Fig. 5. Superimposed profiles of elevation surface positions of rock complexes outside of craters on the floor and southeast edge of Mare Imbrium in a strip 100 km in width along the line: Beer crater -- Bradley Mountains -- Manilius B crater. Even surfaces of complexes: 1. Procellarum; 2. Altaic; 3. Nebula; 4. ancient; 5. suggested prolongations of even surfaces; 6. faults; 7. a line drawn 2 km higher than the cross section of the Moon's figure with the sphere turned to a plane, according to information by G. Shrutka-Rectenstamm (Shrutka-Rectenstamm, Hopmann, 1958). The individual heights are taken from the LAC-41 chart ("Lunar chart," 1960-1964).

Key: a. Beer crater
b. Bradley Mountains
c. Manilius B crater

and the sinking of a mare basin was a multistage process, taking place side-by-side with the filling of the basin by material from outside of a crater (mare), and the last deformations took place after the Procellarum complex had accumulated.

The features of fault systems indicate the multistage development of the basin of Mare Imbrium and formations associated with it. Numerous faults can be seen in the southeastern part of the Mare and to the southeast of it. Here, there are systems in different directions, among which the most expressed is that to the northwest. Faults, disturbing old complexes, can be seen in these systems, but they are interrupted by exposures of an Altaic complex and Ptolemaic craters; there are faults which disturb both old and Altaic and Ptolemaic formations, but are interrupted on the boundaries of the Procellarum complex and Eratosthenian and Copernican craters, and, finally, faults and fissures disturbing the Procellarum complex. Furthermore, among faults of Eratosthenian and Copernican craters and in directions leaving them, there are many disturbances as on older surfaces outside of craters (Copernicus, Pytheas, Lambert, Autolycus, Aristillus). The recurrence of these phenomena during the development of fault systems is also seen in the area of Sinus Iridum, especially on its northern fringe in the Jura Mountains. The

/214

Alpine Valley, the relatively young mare rocks of which are dissected by disturbance parallel to the Valley's older fault boundary, can also be used as an example of multistage development.

J. E. Spurr and G. Fielder noted that the marginal cordillera of the Apennines and craters to the southeast of it have been displaced to the right along faults with a northwest strike (Spurr, 1944, 1945) and the outlines of older craters were more shifted and distorted than younger ones (Fielder, 1963, 1964). Geologic and morphological mapping of the region on a scale of 1:1,000,000 (Trifonov, 1969a) showed that these shift displacements cannot always be considered valid and in places there are none, but, as a whole, this regularity exists. Elements of an old (pre-Altaic) structure are shifted up to 10-15 km, whereas the displacement of Altaic basins, Ptolemaic and Archimedian craters nowhere exceeds 3 km. Cases were also seen where scarps along faults, moving from older to younger formations, were reduced in amplitude. Consequently, both the development of fault systems and displacements along them occurred as a multistage process, reflecting the development of a circular basin and structures associated with it.

The internal zone of Mare Imbrium contains very few large craters of the Eratosthenian and Copernican complexes. On the external zone and on the fringe of the Mare, the number of these craters sharply increases (see Fig. 2, Sheets IV and V). Possibly, the irregularity in the distribution of craters reflects the development of the mare basin in the Eratosthenian and Copernican stages of its geologic history.

All these facts show that the basin of Mare Imbrium was deposited before the accumulation of the Altaic rock complex and continued to develop up until epochs which followed the time when the Procellarum complex accumulated. The filling of the basin by mare material occurred in the process of its evolution.

Mare Claritas (IV, see Fig. 2, Sheets V and VI) is slightly elongated in the northwest, and its diameter varies from 600 to 700 km. Whereas the north and east rims of the basin have sinuous and circular outlines, the west and southwest rims (spurs of the Apennines and Caucasus and the Haemus Mountains) give the basin a polygonal shape. It is in these parts on the rims that the marginal cordilleras are developed. Mare ridges, with all their changes and varieties of strikes, are more often almost parallel to the marginal boundary. In the southern part of the Mare, apart from these there are relatively young fault disturbances.

/215

The surface of the mare basin is almost completely made up of rocks of the Procellarum complex. J. E. Spurr (1945) first noted the lower albedo of mare material on the marginal sections of the basin in comparison with the central one, and on the basis of

correlations of these and others with ray crater systems suggested that the material of the marginal sections was younger. When geologic mapping of the Mare was done on a scale of 1:1,000,000, these changes in brightness were confirmed, and the conclusion on the different age was substantiated by the differences in density of the crater cover. According to M.H. Carr (1966), the youngest member of the mare rock series can correspond in age to the Eratosthenian crater complex (the Tacquet formation and the dark material of the fault region of Littrow). However, the fact that in some areas to the west and east of the crater Tacquet, in the north part of the Mare, and inside the cirque Le Monnier, ray systems of Copernican craters are interrupted, permits it to be assumed that there are widespread younger mare formations. Pre-Procellarum mare material can be seen on limited areas along the boundary of the Mare.

The peripheral belt of basins is changeable in width and is interrupted in some sections. It extends from the cirque Cassini to the cirque Alexander and Lacus Somniorum, and from there to the south to an extensive bay in the north of Mare Tranquillitatis. The belt continues through the northwest part of this Mare to the fault region of Ariadaeus and Mare Vaporum. Within the belt are Altaic, Median and Procellarum rock complexes (see Fig. 2, Sheets V and VI). The composition of the latter, as in Mare Claritas, contains older and younger members (Spurr, 1945; Morris, Wilhelms, 1967; Wilhelms, 1968). The presence of post-Procellarum mare rocks was determined according to the correlation with ray crater systems south of Jansen B and east of Manilius.

The winding nature of mare edges, and, in particular, the occurrence of mare material on the floors of craters of the Le Monnier type, is reason to believe that the basin of Mare Claritas was, to a considerable extent, formed before the accumulation of rocks of the Procellarum complex. But since the surface of Procellarum rocks between Menelaus and Aratus within the Mare is hypsometrically lower than to the south of it, the sinking of the basin relative to the rims continued even later.

The sharply expressed rectilinearity of structural elements and the deformed nature of old craters of the Haemus Mountains owe their existence to the numerous northwest faults. In the south of the Apennines, they are still predominant and combine with faults in other directions (Trifonov, 1969a). The bends of the marginal line of Mare Claritas, to a considerable extent, are determined by these faults, among which there are both pre-Altaic and, to a lesser extent, pre-Procellarum faults, intersecting rocks of Altaic and Ptolemaic complexes. The bend of the Procellarum fault system of Sulpicius Gallus follows that of the marginal line, that is, inherits older structural strikes. A similar continuity in the development of fault systems is seen in /216 eastern fringe of the Mare.

These facts show the multistage development of the Mare Claritas basin and fault systems linked to it and the multistage process in which it was filled with mare material.

Mare Crisium (VII, see Fig. 2, Sheets VI and VII) has an outline similar to a hexagon with rounded points. Linear cut strikes of the margin, at least in the west, better studied half of the structure, repeat the directions of the main fault systems of the margin. Internal and external basin zones are discernible. The external zone has, in plan, the shape of two narrow lens, tapering in the north (?) and in the south. It is divided on the internal zone by a system of relatively young faults and mare ridges, also coinciding in direction with the marginal faults. There is also a strike similarity for mare ridges of the southern part of the internal zone.

Exposures of Procellarum complex rocks occupy the greater part of the basin. Apart from these, in the external zone there are also widespread Median and Altaic formations. Relatively dark sections of the Procellarum surface gravitate to the central and eastern parts of the basin and, as a whole, are more widespread than in Mare Imbrium.

The marginal cordillera is well expressed on the north, west and south rims of the Mare. Two belts of peripheral basins are visible around it. On the western edge of Mare Crisium, north of the Agarum Promontory, the internal belt links up with the external zone of the mare basin. From here, it continues north to Mare Anguis and further to the crater Cleomedes. On the western fringe of the Mare, between the craters Cleomedes and Glaisher W, the belt divides into two "arms," and, between the craters Glaisher and Apollonius B, is broken by transversal disturbances into a series of isolated basins, isometric or elongated either in a longitudinal or transverse direction to the boundary of the Mare. Later, the belt passes towards the northwest from the craters Firmicus and Condorcet.

The external peripheral belt takes in Mare Undarum and Mare Spumans, the northwestern part of Mare Fecunditatis and Mare Tranquillitatis, and west of the craters Lyell and Franz joins with the peripheral belt of Mare Claritas. Then the external belt continues to the crater Geminus, and from there to the eastern part of the visible hemisphere between the craters Hahn and Mare Anguis. The marginal eastern sector of the belt is only expressed by a system of longitudinal, linear disturbances. The external belt differs from the internal one by the large components of its basins. The rectilinear nature of the outlines of individual basins is worthy of note, especially to the west and north of Mare Crisium. The polygonal nature of the belt is caused by a combination of the northwest, northeast and meridional directions of individual basins and their boundaries, coinciding with the predominant strikes of faults in the region (Fig. 6).

/217

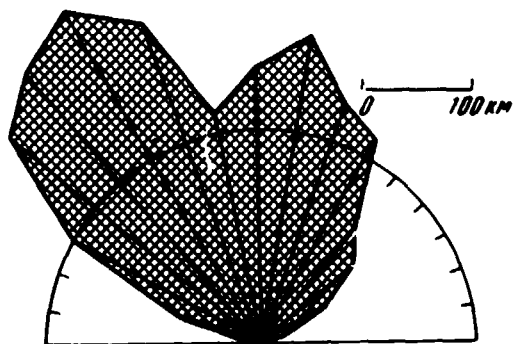


Fig. 6. A combined rose diagram of faults and crater chains of the region bounding the southern half of Mare Crisium. Grouping interval -- 10° . The total extent of faults and crater chains for each direction is shown. The extent of suggested faults is reduced by a factor of 2 in comparison with proven faults.

Altaic, Median and Procellarum mare rock complexes are exposed on the surface within the basins of the peripheral belt (see Fig. 2, Sheets VI and VII). Mare formations of Mare Undarum, the floors of the crater Firmicus and basins to the northwest of it are darker than the Procellarum surface of other areas of the investigated region and probably correspond in age to the youngest members of the Procellarum complex, and possibly partially to the younger mare complex. In this way, the filling of Mare Crisium and basins of peripheral belts by mare material occurred in different places at different times, and was a multistage process.

Analysis of elevation positions of exposures of rock complexes outside of craters within Mare Crisium and on its fringes

indicates that the surfaces of all complexes, as they approach a round basin, gradually bulge up and afterwards in the marginal scarp zone dip sharply inside the basin (Fig. 7). The older the complex outside of a crater, the greater the range of bulging and sinking of its surface. The latter indicates that the sinking of a circular basin and the growth of marginal cordilleras was a multistage process, beginning before the formation of the Altaic, and possibly the Nebular, rock complex, and ending after the formation of the Procellarum complex.

The relative age of fault disturbances, which, depending on their strikes, are grouped into several systems (see Fig. 6) is most important when clarifying the formation history of Mare Crisium and structures related to it. In each of these systems, most faults disturb pre-Altaic formations, but are interrupted in areas where there are many Altaic rocks and Ptolemaic craters. However, the fact that Ptolemaic craters and crater chains are confined to many old faults shows their rejuvenation. There are also faults disturbing Ptolemaic and Altaic complexes. Post-Median and post-Procellarum disturbances coincide in direction with the oldest faults. In this respect, the extended faults Cauchy I, Cauchy II and Apollonius I, stretching along the external peripheral belt of the basins, are especially characteristic. Young faults along the margins of Mare Crisium extend along its boundaries, whose outlines, to a considerable extent, are also

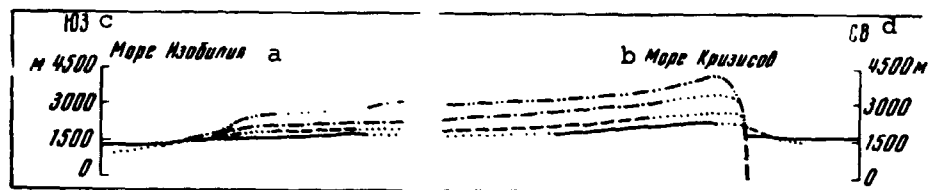


Fig. 7. Combined profiles of elevation positions of surfaces of rock complexes outside of craters on the southwestern edge of Mare Crisium in a strip 150 km wide along the line Taruntius X -- Picard K. Arbitrary symbols are shown in Fig. 5. Individual heights are taken from the LAC-62 chart ("Lunar chart," 1960-1964).

Key: a. Mare Fecunditatis
b. Mare Crisium
c. Southwest
d. Northeast

linked with old disturbance systems. These facts confirm the multistage development of faults systems and, consequently, of the Mare Crisium basin and fringe structures linked with it.

Mare Humorum (VIII, see Fig. 2, Sheet XIII) has round outlines which, as opposed to the mare basins examined earlier, have almost no polygonal elements. The mare ridges gravitate towards the marginal sections of the basin. The peripheral belt of the basins takes in the southern tip of Oceanus Procellarum, the western part of Mare Nubium, Palus Epidemiarum, the area of the crater Clausius, several small basins on the western fringe of the Mare and an extensive, although almost indiscernible, isolated depression between the cirques Mercenius and Letronne.

A geologic description of Mare Humorum is given according to information by M.S. Markov (Markov et al., 1972). The mare basin is made up of rocks of the Procellarum complex, which, near the southwest edge of the basin and on small areas in northern and eastern parts of it are overlapped by younger mare formations. Rocks of Altaic, Procellarum and the youngest mare rock complexes are exposed in the basins of the peripheral belt. It is possible that there are Median formations over limited areas. M. S. Markov notes differences in the manner in which various parts of the belt were filled: in its eastern half, there is a predominating exposure of Procellarum rocks, and in the western, there are Altaic and youngest mare formations.

Arched faults, expressed by scarps and furrows, are clearly visible within the marginal cordilleras and on the edges of the

western and eastern parts of Mare Humorum. Some faults of these systems occurred before the Procellarum complex was formed, others disturb it. To the southwest and northwest of the mare basin, there are rectilinear or slightly curved fault systems, extending at a tangent to the mare basin -- to the northwest and northeast. Some of the faults in these systems were formed earlier than the Altaic complex, whereas others disturb Altaic rocks. The differences in age of faults reflects the multistage development of the Mare Humorum basin.

The boundaries of Mare Cognitum's isometric basin (XXIII, see Fig. 2, Sheets XIII and XIV) are outlined by protrusions of the base among the Procellarum plain, and the arced flexure of the Rhipaeus Mountains, made up of Nebular and ancient rock complexes. Probably, they are relicts of a marginal cordillera. The mare basin is composed of Procellarum and, to a lesser extent, younger mare formations. Only Procellarum mare material is widespread on the surface of the circular basin of Lacus Mortis (XXIX, see Fig. 2, Sheet VI).

Circular Basins of the Mare Nectaris Type

Mare Nectaris (III, see Fig. 2, Sheet XV) occupies the central and northern parts of an extensive (diameter approximately 740 km) basin, which in the future will be called the Mare Nectaris basin in the widest sense of the word. This basin is bounded on the west and southwest by a marginal cordillera of the Altai Mountains, whose scarps replace one another, in a slotted fashion, between the cirques of Sacrobosco and Catharina. The eastern prolongation of the cordillera is traced to the crater Colombo and to the north is lost in the western part of Mare Fecunditatis. Apparently, the basin boundary passes here from Goclenius to Gutenberg G, whereas it is more clearly expressed and extends to Censorinus C and Torricelli. Here, it is hidden beneath Procellarum material of the strait which joins Mare Nectaris and Mare Tranquillitatis. /219

Inside this oval are two ring structures placed one on the other (Khabakov, 1949) displaced towards the southern edge of the depression and merging in the cordillera of the Pyrenees and mountainous regions near the craters Gaudibert, Isadorus-Capella and Theophilus. The external ring continues farther towards the craters Catharina, Polybius, Piccolomini G and Fracastorius B, and the internal one bounds Mare Nectaris in its present-day outlines. The peripheral belt of maria does not have a clear structural expression, although it follows along the numerous small basins of various outlines to the rear of the Altai Mountains and probably continues to the southern part of Mare Tranquillitatis and Mare Fecunditatis. The bay of the latter falls sharply to the south between the craters Petavius and Biot B, and, apparently, becomes a complete part of the belt's composition. The geologic information shown below was borrowed from geologic and

morphological charts and descriptions of the region made by A. L. Sukhanov (1969; Markov et al, 1972).

The internal concentr of Mare Nectaris bounds the basin, composed mainly of Procellarum material. Various sections of its surface differ in lightness, and the darkest are confined to the southern (the vicinity of the crater Y. Ross C and an area north of the cirque Fracastorius G) and the northern (the region of the Daguerre crater) rims of the internal basin. Some differences in the rocks here overlap ray systems of Copernican craters and can be related to the youngest mare formation complex. Rocks of the Altaic complex make up an extensive area in the west of the internal basin, between Theophilus and Beaumont.

There are many exposures of Altaic and Nebular rock complexes in the external zones of the basin outside of areas occupied by crater formations. Median and Procellarum accumulations predominate in the eastern and northern parts of the basin and places associated with them. Depressions of the terrain, elongated along the limits of the basin, correspond to exposures of Median and Altaic rocks. A Nebular complex forms very knolly regions of the Mare's internal concentrs, but in place outside of these ring structures there are few knolls, and it can be looked upon as very old mare material, making up the Mare Nectaris basin. In basins of the peripheral belt, Altaic material occurs in the west and south, and Procellarum material in the north and east.

These facts show the multistage filling of the Mare Nectaris basin by mare material. The multistage development of a structure is shown by analyzing elevation positions of rock complexes and, mainly, by the correlation of fault disturbance systems. Changes in the elevation positions of complexes outside of craters in various sections of a structure do not give an identical result everywhere, but most often a gradual bulging of Nebular and Altaic complexes is seen from the rear to the crest of a cordillera and their sharp dip inside the basin. The range of these deformations is greater for a Nebular complex than an Altaic one. Hence, in the basin of the Mare east of Rothmann G, individual heights of the Altaic complex fluctuate, according to the LAC-96 chart, from 2500 to 3300 m, and the Nebular by a few hundred meters more. On the floor of the Rothmann G cirque and alongside it, that is, on the cordillera crest, the Altaic surface lies at a level of 4000-4200 m, gradually dropping in the west to 3000-3300 m. The Nebular surface on the crest of the Altai ridge reaches heights of 4500-4800 m, and drops in the west and southwest to 3000-3600 m. These correlations show the nonuniform bulging of the Altai ridge relative to the Mare basin, occurring both before and after the accumulation of the Altaic rock complex. The maximum bulge occurs on the crest of the cordillera.

/220

There is a predominance of northwest disturbances, radial or at a tangent to the concentrs of the mare basins, among tectonic

faults in the Mare Nectaris basin and the its vicinity. Probably, it is these faults which determine the tapered nature of the boundaries and the rectilinear nature of the northeastern edge of the basin. In the northern part of the basin and its environments, some faults only disturb pre-Altaic or pre-Median rocks, and others continue to Median and, frequently, Procellarum surfaces. To the southeast of Mare Nectaris, faults of this direction are primarily of Pre-Altaic and Altaic age; however, the fact that many of them are confined to Ptolemaic and Archimedian craters indicates a subsequent renewal of activity. Similar manifestations of the multistage formation of fault systems are also seen for northeast and meridional disturbances, although most of them were deposited and developed in a pre-Altaic time.

Mare Orientale (II, see Fig. 2, Sheets XI and XII) is one of the most expressive structural formations on the Moon. The main, oval boundary of the basin is represented, to a considerable extent, by the Cordillera range, the D'Alembert Mountains, the mountains in the area near the crater Shaler and their western prolongations. There are two more clear centers inside the basin: the external one (the Rook Mountains are part of it) and the internal, separated from the external by Mare Veris and Mare Pacis. Possibly, there is another system of broken and poor elevations closer to the center of the basin, strictly isolating Mare Orientale from the remaining parts of the basin. Beyond the main cordillera west and east of the Mare basin, there are, as it were, one or two belts of indistinct depressions which could be considered peripheral. There are no similar formations to the north or south of the basin. The specifics of the Mare Orientale basin, which distinguish it from the Mare Nectaris basin and even more from all earlier-examined structures, is the significant height and width of the two internal cordilleras, due to which the external zones of the basin appear as relatively narrow ring depression systems.

The central part of the Mare Orientale basin is composed of formations of the Procellarum² complex, which, to the north, are probably replaced by Median. Between this part of the basin and the first clear internal center, there is a region of predominantly Altaic and Nebular (?) rocks. Between the two internal centers, there is a system of narrow depressions, composed of Procellarum and Nebular (?) rock complexes. Between the external center and the boundary of the whole basin, there are widespread Procellarum, Altaic and Nebular (?) complexes on the surface. The hypothetically isolated Nebular complex in places preserves the

² Possibly, there is also a complex of the youngest mare formations in Mare Orientale, Mare Pacis, Mare Veris and Mare Autumni. But it is impossible to isolate it or, even more, determine which members of the Procellarum complex are most widespread, with the data available at present.

outlines of mare formations, only differing from the Altaic by the large number of small, covering craters, domes and fault disturbances. It is possible that this same Altaic complex was formed and destroyed by young structural elements. Formation features of the surface around the mare basin, are determined to a considerable extent by the ejection of material from the area of its floor. The ejections either occurred when the basin was formed or during one stage of its development. In places, the linearity of ejection makes it difficult to distinguish them from structural elements caused by faults. /221

Perhaps the region near the Mare Orientale basin is the most graphic confirmation of a situation when the number of faults on the Moon's surface increases as the circular mare basins are approached, but fault strikes are not subordinate to the "radial", but the general planetary regularity. Almost all faults of the region examined extend along a northwest, northeast and meridional direction and, as a rule, are radial and at a tangent to centers of the basin. In places, especially on the northern fringe of the basin, faults of various directions intersect, forming a system of rhomboid blocks. Most faults occurred before or during the Altaic stage, but some also intersect the Altaic complex. Hipparchian, Ptolemaic, Archimedian, and, to a lesser extent, Eratosthenian and Copernican craters chains situated among them indicate the rejuvenation of old faults. Later stages of structure development are also fixed by new positive formations (volcanic and extrusive domes?), observed by A. L. Sukhanov on the surface of the internal cordilleras of the mare basin.

Mare Moscoviense (XI, see Fig. 2, Sheets VIII and IX), as a whole, has round outlines, although the southwestern and, partly, the northeastern boundaries of the basin are aligned by northwestern faults. They represent a more developed disturbance system in the region examined. Besides this, there are widespread faults in a northeastern and, to a lesser extent, meridional direction. Normally, faults of all three systems are rectilinear and only in some areas are the rings of marginal elevations curved in an arced fashion parallel to the strike of the marginal line. Arced elevations adjoin the southwest side of the basin -- relicts of a ring separating the internal and external zones.

The internal zone of the Mare is composed of rocks of the Procellarum, Median and Altaic complexes. Besides these, in the external zone there is a Nebular complex, partly having features of old mare formations, disturbed by more recent craters and faults. Exposures of the Procellarum complex gravitate towards the eastern part of the basin. Among faults in Mare Moscoviense and its vicinity, there are pre-Nebular, pre-Altaic and pre-Median disturbances. These indications of a multistage development are particularly clearly shown in the northwestern disturbance system. There are short crater chains of Ptolemaic and Archimedian complexes along several old meridional, northwest and, to a lesser extent, northeast faults.

Mare Smythii (XII, see Fig. 2, Sheets VII and XVI) is not bounded by clearly expressed cordilleras. Nor is there a complete belt of peripheral basins around it. An analog of the latter could be the basin to the northeast of Kästnor, Mare Maginis and the area to the southeast of it. Mare Smythii is mainly composed of Procellarum complex rocks. Altaic and, in small areas, Median formations appear in the south of the basin. Possibly, the widespread area of the Altaic complex is the external zone of the Mare. Procellarum, Altaic and, to a lesser extent, Median rock complexes appear on the surface in isometric and elongated basins surrounding Mare Smythii.

/222

Mare Somniorum (XX, see Fig. 2, Sheet XVIII) is bounded on its whole length by elevations of marginal crests. Northeast, poorly expressed northwest and meridional disturbance systems determine the polygonal nature of this basin, which is approximately hexagonal in shape with arced flexures at the summits. A small, oval internal center is displaced towards the eastern edge of the basin, isolating its internal zone. It is made up of rocks of the Procellarum complex. Nebular, Altaic, Median and Procellarum formations are on the surface in the external zone, and the Nebular complex has the appearance of an old mare plain. Most fault disturbances of the basin and its surrounding area occurred before and during the Nebular stage. Some southwest faults disturb the Altaic complex of rocks, and crater chains and coupled craters of Hipparchian, Ptolemaic and Archimedian complexes extend along meridional disturbances.

Mare Humboldtianum (XV, see Fig. Sheets VI and XX) is a special formation in the type of basin examined, since the gigantic ring structure of Belkovich is superimposed on its northeastern rim. According to morphological indications, it should be related to the large volcano class (there is a ridge and arced faults), but possibly it could be a mare type basin, and the appearance of it marked one of the stages in the development of Mare Humboldtianum. The poor quality of photographs of the region makes it difficult to answer this question definitely. In any case, the structural elements of the mare break off at its boundary with Belkovich and are not continued on its floor, composed mainly of Altaic rocks.

Mare Humboldtianum is bounded for a considerable extent by a marginal cordillera which, as it moves from the Mare basin to the southwest, is replaced by a wide arced peripheral belt. It consists of individual basins, isometric or elongated in a northeast direction along the prevailing fault system. These basins contain Altaic and, to a lesser extent, Median rocks. Mare Humboldtianum is made up of material of Procellarum, Median, Altaic and Nebular complexes, and the relatively young formations gravitate towards the western part of the basin. Possibly, the fact that they taper away as they approach the Belkovich structure

and disappear in the same direction of the peripheral belt of basins is interlinked and reflects a longer evolution of the southwest part of the mare basin in comparison with the northeast, the development of which was interrupted by the formation of Belkovich.

Northeastern faults predominate on the southwest fringe of the mare. To the east they are replaced by northwest one. Northwest and meridional disturbances combine on the north side of the basin. The presence among these faults of pre-Hipparchian and pre-Altaic and post-Ptolemaic disturbances allows one to assume that the whole structure had a multistage formation.

Circular Basins of the Korolev Thalassoid Type

The Korolev thalassoid (X, see Fig. 2, Sheets I and X) was first recognized on the Moon's surface due to the flight of the Soviet Zond 3 automatic station, and is a round mare basin with a diameter of approximately 370 km. The basin is surrounded by a cordillera which is not as well expressed on the north side as in other places. Inside the basin can be seen broken relicts of a second, more angular cordillera with a diameter of approximately 190 km. The basin's peripheral belt is not expressed. The external zone of the basin (between the main and internal cordilleras) is composed of Nebular and, to a lesser extent, Altaic rock complex formations. There are more rocks of an Altaic complex exposed in the internal zone than Nebular ones. Rock exposures of the Nebular complex inside the basin have a relief similar to a mare type surface, changed by subsequent processes. The cordilleras are arbitrarily related to the oldest rock complex, although there may be younger formations in them. /223

There are not many fault disturbances inside the basin. Faults of different ages (from pre-Altaic to presumably post-Procellarum), bounding the internal zone, are better expressed here than others. The faults extend mainly in almost meridional directions on the sides of the basin, although to the north and south some of them turn back to northwest or northeast directions and, in individual areas, are intersected at acute angles in the same way as in the north and south of the basins of Mare Crisium and Mare Orientale. There are disturbances from pre-Nebular to post-Ptolemaic among faults in the vicinity of the Korolev thalassoid. They belong to the same systems and reflect the multistage nature of their formation. Since these systems are linked with the basin's limiting structure, it can be assumed that its development was also multistage and took place side-by-side with the filling of the basin by mare material.

Basins of the Korolev thalassoid type -- This is a more numerous class of structural forms (Table 2) than mare basins

described earlier. Therefore, it is not necessary to examine each thalassoid, since many of their features are repeated from one basin to another.

All basins of this type are bounded, although not always completely, by a more or less expressed cordillera. Some are round, others have polygonal features. The most clearly expressed polygonal form is in the Lorentz thalassoid (XIV, see Fig. 2, Sheets II and II), bounded by fractures and having a quadrangular shape.

In the basins Hertzprung (V, see Fig. 2, Sheets II and XI), Apollo (VI, see Fig. 2, Sheet X), in the region of the Schickard cirque (XIII, see Fig. 2, Sheets XIII and XXI), Birkhoff (XIV, see Fig. 2, Sheets I, II and XIX), Schrödinger (XVII, see Fig. 2, Sheet XXIV), Bailly (XIX, see Fig. 2, Sheet XXI), Poincaré (XXII, see Fig. 2, Sheet XVIII) and Campbell (XXVII, see Fig. 2, Sheet IX), besides the main cordillera there is an internal one. It does not form a complete ring in all basins, but consists of individual arced and, to a lesser extent, angular ridges. Around the basins Apollo, in the region of Schickard, Bailly and Mendeleyev (XXI, see Fig. 2, Sheets VIII and IX) are small, broken exposure of mare rocks (Altaic complex), which can be looked upon as part of peripheral belts.

In all basins of the Korolev thalassoid type, apart from the D'Alembert basin (XXXIII, see Fig. 2, Sheet IX), there are no less than two different age rock complexes outside the craters. These are mostly rocks of the Altaic and Nebular complexes, and exposures of the latter often preserve signs of the mare surface. In basins of the region near Schickard, Poincaré, Campbell and Milne (XXX, see Fig. 2, Sheet XVII) there is also a Median complex. Small exposures of Procellarum formations are discernible in the Schrödinger and Milne basins. Procellarum or Median rocks make up a considerable part of the internal zone of the Apollo basin. /224

It is characteristic that in all thalassoids which have a an internal cordillera, younger rocks are either widespread in the internal zone or, if both zones are composed of complexes of the same age, relatively young formations occupy larger areas in the internal zone. /225

Basin XXIV (see Fig. 2, Sheet XIV) is distinctive. Relicts of its marginal cordillera form a crescent on the eastern edge of Mare Nubium, whereas Procellarum and Median mare material covering the floor of the basin make up a complete whole with rocks of this Mare. An arced system of mare ridges, representing, as it were, a prolongation of the marginal cordillera of basin XXIV, emerges on its surface. Possibly, Sinus Iridum (XXXIV, see Fig. 2, Sheet IV) and several other less clearly expressed formations belong to similar structural forms. /226

TABLE 2. THE MOST IMPORTANT CHARACTERISTICS OF CIRCULAR MARE BASINS OF THE MOON

No. of basin	Name	Approximate coordinates of the center	Diameter dimensions in km			Mare rock complexes on the surface			Indications of length of development	Type of basin
			a	b	c	a	b	c		
I	Mare Imbrium	34°N lat, 16°W long	~2000	1100	730	M, Pr, Md, Al, (Nb?)	M, Pr, Pr, Md, (Nb?)	(Pr?) Pr, Pr, Md, (Nb?)	++	1
II	Mare Orientale	20°S lat 95°W long	?	840	{ 570, 410 } { ~240 }	(Nb?)	Pr, Al, (Nb?)	Pr, Al, (Nb?)	+	2
III	Mare Nectaris	16°S lat, 33°E long	?	740	{ 480 } { 400 }	Pr, Md, Nb	Pr, Md, Al, Nb	Md, Al, Nb	++	2
IV	Mare Claritas	25°N lat 19°E long	~1300	670	420	M, Pr, Md, Al	M, Pr	Pr, Pr	++	1
V	Hertzsprung thalassoid	0°N lat, 120°W long	?	520	230	Al, Nb	Al, Nb	Md, Al, Nb	—	3
VI	Apollo thalassoid	35°S lat, 152°W long	?	460	~100	Al, Nb	Al, Nb	Pr, Md, Al	—	3
VII	Mare Crisium	16°N lat 59°E long	{ ~1150 } { ~700 }	430	340	Pr, Md, Al, (Nb?)	Pr, Md, Al	Pr, Pr	++	1
VIII	Mare Humorum	24°S lat, 38°W long	~780?	400	—	Pr, Md, Al	M, Pr, Al	—	—	1
IX	Nameless	44°N lat 104°E long	—	~390?	—	—	Al, Nb	—	—	3
X	Korolev thalassoid	4°S lat, 158°W long	—	370	190	—	Al, Nb	Al, Nb	—	3
XI	Mare Moscovense	25°N lat 145°E long	—	360	210	—	Pr, Md, Al, Nb	Pr, Md, Al	—	2
XII	Mare Smythii	1°S lat, 87°E long	?	350	260	Pr, Md, Al, (Nb?)	Pr, Md, Al	Pr	—	2
XIII	Nameless	55°S lat, 45°W long	?	320	170	(Md, Al?)	Md, Al	Md, Al	—	3
XIV	Lorentz thalassoid	35°N lat 98°W long	—	300	—	—	Al, Nb	—	—	3
XV	Mare Humboldtianum	57°N lat 81°E long	~600?	290	—	(Md?), Al, Nb	Pr, Md, Al	—	—	2
XVI	Rikhoff thalassoid	58°N lat 149°W long	—	290	100?	—	Al, Nb	Al	—	3
XVII	Schroderinger thalassoid	70°S lat, 131°E long	—	290	100	—	Al, Nb?	Pr, Md, Al	—	3
XVIII	Planck thalassoid	55°S lat, 131°E long	—	270	—	—	Al, Nb	—	—	3
XIX	Baily thalassoid	67°S lat, 70°W long	?	270	130	(Al?)	Al, Nb	Al	—	3
XX	Mare Somniorum	35°S lat 163°E long	—	260	105	—	Pr, Md, Al, Nb	Pr	—	2
XXI	Mendeleev thalassoid	4°N lat 140°E long	?	250	—	(Al?)	Al, Nb	—	—	3
XXII	Poincaré thalassoid	53°S lat, 138°E long	—	250	130	—	Al, Nb	Md, Al	—?	3
XXIII	Mare Cognitum	8°S lat 25°W long	—	210	—	—	Pr	—	—	1
XXIV	Nameless	22°S lat 7°W long	—	200	—	—	Pr, Md	—	—	3
XXV	Gagarin thalassoid	22°S lat 148°E long	—	200	—	—	Al, Nb	—	++	3
XXVI	Nameless	58°N lat 100°W long	—	200	—	—	Al, Nb	—	—	3
XXVII	Campbell thalassoid	44°N lat 151°E long	—	190	130?	—	Nb	Md, Al, Nb	—	3
XXVIII	Galois thalassoid	1°S lat 153°E long	—	180	—	—	(Al?), Nb	—	—	3
XXIX	Lacus Mortis	45°N lat 27°E long	—	170	—	—	Pr	—	—	1
XXX	Malpe thalassoid (?)	32°S lat, 114°E long	—	220	—	—	(Pr?), Md, Al, Nb	—	—?	3
XXXI	Pasteur thalassoid	13°S lat, 106°E long	—	180	—	—	Al, Nb	—	—	3
XXXII	Lamont thalassoid	43°N lat 120°W long	—	170	—	—	Al, Nb	—	—	3
XXXIII	Alamert thalassoid	53°N lat 163°E long	—	170	—	—	Al	—	—?	3

Note. a. A peripheral belt (or belts) of depression; b. a basin in the boundaries of the main cordillera (or its external zone when there are internal cordilleras); c. internal zone (or zones) of the

[continued on following page]

Note to Table 2, continued

basin. Complexes are shown which are most widespread in each zone of a circular basin; + basins with indications of a multistage development of fault systems; ++ basins where the multistage development is determined, apart from this, by deformations of even surface of complexes outside of craters; 1. basins of the Mare Imbrium type; 2. basins of the Mare Nectaris type; 3. basins of the Korolev thalassoid type.

The relationships between thalassoids and fault disturbances varied. Considerable fault systems are in no way linked with some depressions. Faults in the Hertzsprung thalassoid region and basins around the cirque Fabricius (IX, see Fig. 2, Sheets VII and VIII) are on the prolongation of disturbance systems leaving the large Mare Orientale and Mare Humboldtianum. Some of these faults are bounded by exposure of mare rocks in the basins examined, and others intersect them. In a number of cases, there are also connections between mare basins and faults, which allows one to assume their paragenetic link. We shall examine these cases in more detail.

In the region of the Apollo basin, extended fault systems have been determined on the west, east and north sides. On the west and east sides, the faults extend approximately along the basin boundaries. On the north side and to the north of it, they are intersected by submeridional and northwest and, to a lesser extent, northeast disturbances subordinate to them. The submeridional system continues farther to the north, where it joins the system of the south limit of the Korolev thalassoid. As a whole, a diagram of intersecting faults is similar to that on the southern boundary of Mare Orientale. In the systems examined, there are disturbances from Nebular to post-Ptolemaic and, possibly, post-Procellarum. This indicates the multistage development of systems, probably reflecting the multistage development of the mare basin.

In the vicinity of the Schrödinger basin, faults are situated primarily in an arched fashion, parallel to the basin's boundaries. However, on the south and east fringe and to the northwest of the basin, some of these faults become rectilinear, forming a firm northwest strike system. Among the faults there are pre-Altaic, post-Ptolemaic, and Eratosthenian and Copernican. Some northwest faults become almost latitudinal. There are crater chains of Ptolemaic-Archimedian age and, to a lesser extent, Eratosthenian-Copernican age on their strike. The obvious link between fault systems and the basin structure (see Fig. 2, Sheet XXII) indicates, when there is a multistage formation of

fault system, that the development history of a thalassoid is just as complex.

The most complex combination of disturbances in various directions is shown in the region of the Mendeleyev basin. There are faults in different directions on its west side, and a predominance of disturbances stretching along the boundary of the basin and determining the shape of this boundary. On the east side of the basin, there are intersecting northwest and northeast disturbances, becoming two submeridional systems in the south. Normally shorter northwest disturbances intersect them and combine with them. Meridional faults here are relatively rare and less expressive. As a whole, the combination of these systems is similar to the disturbance diagram of the northern boundaries of the Mare Orientale basin and, as it were, are a mirrored reflection of this diagram.

Within one and the same fault systems there are pre-Nebular, (227) (?), pre-Hipparchian, pre-Altaic and post-Ptolemaic disturbances. Ptolemaic and Archimedian crater chains are found along some faults of relatively old formation. Consequently, in this case the multistage development of fault systems and, probably, the basin structure linked with them is shown sufficiently clearly. The more westerly of two meridional fault systems leaving the Mendeleyev basin to the south reaches the boundaries of the Gagarin basin (XXV, see Fig. 2, Sheet XVIII) and here turns back to the southwest in accordance with the strike of its northwest side. This bend suggests that there is a link between faults and the structure of the basin. Since there are disturbances from pre-Hipparchian to post-Ptolemaic in the system examined, it is very probable that the Gagarin basin, laid down in Nebular time, continued to develop until the end of the Ptolemaic stage.

The northeast faults on the sides of the Poincaré basin determine its elongation in that direction. In this fault system there are pre-Nebular, pre-Hipparchian and post-Ptolemaic disturbances. probably, the development of the basin was multistage.

The Milne and D'Alembert basins, as it were, have the same old formation as the mare structures examined. The relatively young age of faults on the sides of these basin possibly reflects later stages of their development. The fact that these faults extend approximately along the sides of basins relates them to crater formations, in spite of their considerably large size.

Irregularly Shaped Maria

Maria or parts of them which are in peripheral belts around circular basins have been examined in previous sections. Here we shall only touch upon irregularly shaped, extensive mare basins

which are not part of peripheral belts. These basins form two elongated zones stretching from the northwest to the southeast. One of them takes in the northwestern, central and southern parts of Oceanus Procellarum (XXXV, see Fig. 2, Sheets III, IV and XIII), the central and southern parts of Mare Nubium (XXXVI, see Fig. 2, Sheets XIII and XIV) and possibly continues farther to the southwest in the form of small isolated exposures of old mare formations. The other zone occupies extensive parts of Mare Tranquillitatis (XXXVII, see Fig. 2, Sheets VI and XV) and Mare Fecunditatis (XXXVIII, see Fig. 2, the same) and continues to the southeast to Mare Australe (XXXIX, see Fig. 2, sheets XVI, XVII and XXII), and isolated exposures of mare rock complexes adjoining them.

In both zones, side by side with exposures of a Procellarum complex, in places clearly dividing the subcomplexes into lower and upper, there are Median and Altaic formations. The Median complex forms comparatively small areas in the northern part of Oceanus Procellarum and the Mare Australe region. The Altaic complex is more widespread: in the northwest fringe of Oceanus Procellarum, in small isolated basins southeast of Mare Nubium (up to the Boussingault crater region), and in the Mare Australe region. Post-Procellarum mare formations are seen in a few, small areas. Obviously, the filling of these basins by mare material covered the formation time of all mare rock complexes shown.

The persistent nature of strikes of both mare zones allows one to assume a link between them and fault disturbances. To the north of Oceanus Procellarum and southeast of Mare Nubium, disturbance systems with a northwest strike are in fact visible. They are particularly well seen in the triangle between the Purbach-Regiomontanus-Walter crater chain, the cirque Clavius and the southwest tip of Mare Nubium. Here there are several fault systems and individual faults, among which there are a few pre-Nebular and more numerous pre-Altaic, pre-Median, pre-Eratosthenian and Copernican formations. Mare ridges, particularly numerous in the southern half of Oceanus Procellarum, extend in this same northwest direction. Several northwest ridges, situated directed on the prolongation of faults, are visible between Mare Nubium and Oceanus Procellarum.

/228

The link between fault disturbances with a northwest strike are expressed even more clearly in the Mare Tranquillitatis, Mare Fecunditatis and Mare Australe zone. The largest fault system in the Haemus Mountain region adjoins Mare Tranquillitatis from the northwest (Trifonov, 1969a). It is hardly continued inside the mare basin, but further to the southeast is again expressed as disturbances in the Pyrenees region. This system dies out towards the southern end of Mare Fecunditatis, but southeast of the Petavius cirque, northwest faults, reaching the Mare Australe

region, are visible on the prolongation of it. To the southeast of it, northwest faults are again clearly expressed up to the boundaries of the circular basin Schrödinger.

A deep fault system, taking in the Rheita Valley and reaching the southwest end of Mare Australe, extends from the southern end of Mare Nectaris parallel to the disturbances mentioned. There is another large disturbance system on the other side of the mare basin zone examined. It begins on the east and southeast edges of Mare Claritas, extends between Mare Crisium, on one side, and Mare Tranquillitatis and Mare Fecunditatis on the other, and dies out east of Langrenus.

A succession of pre-Altaic and post-Altaic faults, but of pre-Procellarum age, is clearly seen in the region of the Haemus Mountains between the Apennines and the cirque Julius Caesar (see the description of Mare Claritas and Mare Imbrium). In the Pyrenees region, there are pre-Median, post-Median and post-Procellarum disturbances of the northwest strike. Pre-Ptolemaic, post-Ptolemaic and post-Procellarum faults can be seen southeast of Petavius. Between Mare Australe and the Schrödinger basin there are pre-Hipparchian, post-Hipparchian, but pre-Ptolemaic and Eratosthenian disturbances. Obviously, the whole disturbance system was a multistage development from Nebular to post-Procellarum times.

Similar indications of the multistage development are also shown for the two other northwest disturbance systems mentioned. There are both pre-Ptolemaic and post-Ptolemaic, but pre-Median disturbances in the fault system between Mare Nectaris and the western end of Mare Australe. To the west and south of Mare Crisium (see this description), there are faults disturbing pre-Hipparchian and Nebular complexes, but not affecting the Hipparchian; disturbing all pre-Altaic structural forms, but not continuing to the Altaic surface; disturbing Altaic, but not Median or Procellarum formations. There are also post-Procellarum faults in this system. The Cauchy Fault and disturbances in the Taruntius region, which are of a Procellarum, but probably post-Eratosthenian and Copernican age, extend parallel to them, somewhat to the southwest.

/229

There is no clear predominance of northwest strike forms among mare ridges of the zone examined, as in Oceanus Procellarum. Nevertheless, northwest mare ridges are quite numerous in the central part of Mare Tranquillitatis and Mare Fecunditatis. Some of them are directly on the prolongation of fault disturbances.

The area occupied by individual exposures of the Altaic complex on the far side of the Moon to the west and south of the Apollo basin is considerably less than the two zones described (see Fig. 2, Sheet X). Altaic material makes up the crater floors and forms irregularly shaped fields among Nebular formations. As

a whole, the structural diagram of the region is similar to the Mare Australe region, although there is more mare material in the latter. There are no signs whatsoever of linearity in the distribution of mare complexes.

Another region where Altaic formations are widely distributed is on the near side close to the north pole. Here, Altaic material also makes up crater floors and extensive irregularly shaped fields among Nebular complex exposures. It is not clear whether this region can be looked upon as an independent isometric distribution zone of old mare formations or as a remote part of a peripheral belt of basins are Mare Imbrium.

Thus, rock complexes of different ages are seen in almost all mare basins, indicating the multistage nature in which the basins were filled by mare material. For many and, in any case, for all typical basins and those of each group which can be studied more carefully, the development of their structure occurred side by side with the filling of the basins with mare material. In the majority of cases, this indicates the multistage nature of development of fault systems, paragenetically linked with mare basins. For Mare Imbrium, Mare Claritas, Mare Crisium and Mare Nectaris, where hypsometry is quite accurate, this conclusion is confirmed by direct information on the surface deformations of complexes outside of craters on the boundary of the basin and within the marginal cordillera. The morphological similarity between other circular maria and those for which the multistage formation has been proved, allows one to assume that their development also took place side by side with the filling by mare material.

Consequently, resolving the question of the length of the formation of mare basins leads one to determine the length of formation of mare rock complexes filling them. If these complexes were formed directly after each other (in the geologic sense) the basins could be of impact origin. If the basins were successively filled by mare rock complexes over a long geological time, the basins undoubtedly belong to endogenous formations.

Multistage Development as a Reflection of the Long-Term One

/230

Before age was determined radiologically, all estimations of the length of formation of lunar rock complexes were made according to the number of craters on the surfaces of different complexes. This area of research has not lost its significance even today.

One of the first such attempts was made by A.V. Khabakov (1960). According to him, "... beginning with the assumption that an endogenous origin is more probable for lunar mare basins and

for the majority of large cirques and craters, one can take as a base for estimations the normal length of activity of each volcanic center assuming that processes accelerate as they approach the maximum volcanic and tectonic activity and slow down when volcanism becomes extinct" (p. 288). Hence, it follows that the length of the Copernican periods is probably more than 2.5-5 million years, and, as a whole, "relief formations preserved on the Moon could, mainly to the physical transformations of matter in its interior, be formed during 100-200 million years" (the same, p. 290).

American researchers in estimations of a similar type, made with the help of orbital photographs, began with the assumption of the impact origin of lunar craters (as a rule, craters with a diameter less than 20-30 km are taken into account). The calculations depended on determining the present-day speed of meteorites, the density of the meteorite flux and the impact effects of falling bodies. In the past, this information with those or other corrections has been extrapolated. When there is no change in these values, the age of Aristarchus is Tertiary, Tycho is Mesozoic, and Copernicus is early Paleozoic (Hartmann, 1967, 1968; Kopal, 1969).

On the whole, there are significantly more small craters on the surface of the Procellarum complex, and their density differs considerably in various maria and parts of maria; the density of covering craters on highland plains, that is, old mare surfaces, is even higher (Trask, Rowan, 1967).

The most complete estimation of the relative age of lunar maria according to the density of covering craters was made by W. K. Hartmann and J. A. Wood (1971), who analyzed more than 30 mare basins on the Moon. They separately resolved questions of determining the age of material filling basins and the age of the basins themselves, which was estimated according to the density of craters on the their fringes. Craters less than 2 km in diameter were not examined since, according to these authors, this got rid of the uncertainties caused in the calculations by secondary impact and endogenous craters.

The calculations done allowed W. K. Hartmann and J. A. Wood to divide basins into several age generations. Similar estimations have also been carried out by other researchers (Baldwin, 1969; Stuart-Alexander, Howard, 1970), partly with these and partly with other methods. These authors unanimously admit that the youngest basins are Mare Orientale, Mare Imbrium and the Schrödinger thalassoid, and the oldest basins are Mare Smythii, Mare Tranquillitatis, Mare Nubium and Mare Fecunditatis. However, there are great divergences in the estimations of the relative age of other basins. Thus, W. K. Hartmann and J. A. Wood, and also D. Stuart-Alexander and K. Howard believe that Mare Claritas is one of the oldest and, according to data on crater density,

carried out by P. Baldwin, it is much younger. W. K. Hartmann and J. A. Wood believe the Mare Crisium basin is an old formation, /231 and R. Baldwin, D. Stuart-Alexander and K. Howard believe it to be one of the youngest formations. There are great divergences in the estimations of the relative age of Mare Humorum, the Apollo thalassoid and a number of other basins.

According to W. K. Hartmann and J. A. Wood, the basins were filled a considerable time after they were formed. The Procellarum complex of Mare Crisium, Mare Humorum, Mare Imbrium, Mare Nectaris and Mare Orientale are characterized by similar mean values of covering crater density. On an average, the filling of Mare Humboldtianum, Mare Tranquillitatis and Mare Smythii is noted for its great density (apparently due to the distribution in them, besides Procellarum, of old mare formations). The filling of Mare Moscoviense, the thalassoids Schrödinger, Apollo, Hertz-sprung, near Schiller, Milne, Poincaré, and Bailly is even older. Apparently, the mean density of the covering craters corresponds to that of the Altaic rock complex. It is on the same order as the crater density on ejecta from Mare Orientale, Mare Imbrium and the Schrödinger thalassoid. According to W. K. Hartmann and J. A. Wood, these ejecta from Mare Orientale determine the age of the surface of the Apollo and Hertzsprung thalassoids.

The ejecta fields around Mare Orientale and Mare Imbrium have been noted by many researchers who looked on them as the result of impact formations of basins. If ejecta are in fact linked with the formation stage of the investigated basins, the latter were formed during the formation of the Altaic rock complexes, and older formations are not exposed within basins or around them. It can be assumed however that enormous ejections were only a stage in the tectonic and magmatic evolution of mare basins, and in places a structure shows through the ejecta which occurred at older stages of development of these maria. Be that as it may, relatively young elements play a significant role in the formation of Mare Orientale and Mare Imbrium.

The floor of the Pingret basin has the highest crater density, which agrees with the old appearance of its surface.

The radiological age of crystalline rock in the area where Apollo 11 landed was 3.8 ± 0.6 billion years (Science, 1971), and Apollo 12 -- approximately 3.3 billion years (Wilhelms, Davis, 1971). Among rocks from the landing site of Apollo 12 there is sample No. 12013, which is a rhyolitic injection into breccia. The age of the rhyolite was determined as 4.0 ± 0.05 billion years (Albee et al., 1970). Since there is a similar rhyolitic mesostasis in crystalline rocks from Apollo 11, it can be assumed that the formation of mare rocks also took place during this rhyolitic injection. It is true that we do not know whether they belong to the Procellarum or older mare complexes.

According to geologic information, the Apollo 11 landing site is composed of lower Procellarum, and at Apollo 12 there are upper Procellarum subcomplexes. In this way, information from radiological determinations agree with the relative age of rocks and indicate a longer formation time of the Procellarum complex as a whole. The number of small craters seen on its surface could have been caused in the interval of time from the complex formation epoch until the present day with a reduced density of the meteorite flux with time.

Determinations of the radiological age of a thin fraction of regolith and breccias on the surface of lunar maria gave values of 4.6 ± 0.4 billion years for rocks in the Apollo 11 landing site (Science, 1970), 4.5-4.6 billion years for breccia No. 12013 (Albee et al., 1970) and $4.25-4.85 \pm 0.75$, the mean according to isochrone $4.45-4.65 \pm 0.5$ billion years for the Luna 16 landing site (Vinogradov, 1971). The thin fraction and the breccias consist mainly of more or less altered fragments of crystalline mare rocks, to a lesser extent of fragments of other magmatic formations, and to an even lesser extent of meteoritic matter and other admixtures. Probably these determinations reflect the age of the oldest components and show that magmatic activity in various regions of the Moon, including various mare basins, began approximately at the same time: $4.5-4.6 \pm 0.5$ billion years ago. /232

The interval from 4.5 to 3.8 billion years is a sufficiently long interval of geologic time for pre-Procellarum mare rock complexes to be formed. As yet, we do not have their radiologically determined ages. An estimation of their absolute age according to the density of covering impact craters entails great difficulties. As it increases, a larger number of earlier formed craters was destroyed or overlapped by newly formed ones. Therefore, it is impossible to calculate the overall number of impacts. There is even more uncertainty in estimating the laws governing the decrease of the meteorite flux over time.

In spite of these complications, quantitative evaluations of the length of formation of old mare complexes can be suggested. If the meteorite flux decreased slowly from the formation time of the Procellarum complex, it could scarcely have changed instantly immediately before this, and therefore a sufficiently long time would be required to create an increased number of craters on old mare surfaces -- at least tens of millions of years.

Pre-Hipparchian, Hipparchian, Ptolemaic and Archimedian crater complexes differ considerably in the degree of preservation of the initial relief. Probably, one of the most important factors of their transformation was the erosive effect of meteorite impacts. The concepts shown of the gradual change of the meteorite flux allows one to assume that there are considerable

differences in the age of craters of various complexes and, consequently, mare rock complexes which alternate with them.

Apparently, on the Moon there are both meteorite and volcanic craters. Whatever their quantitative ratios are, the observed differences of the density of craters covering one or another mare rock complexes indicate the geologic length of their formation. Probably, the final stages of formation of complexes following one another occur not less than tens of millions of years later, and the whole combination of mare rocks formed over hundreds of millions of years. The formation of the structure of mare basins took place side by side with their filling. For example, in Mare Imbrium it began before the Altaic stage and ended after the Procellarum, continuing for a very long time. Many mare basins, where there are only pre-Procellarum formations, could hardly have developed in such a long time; however, these also, if one is to judge by the different age of filling rock, ought to have been formed in not less than tens of billions of years. This continuous development of basins contradicts the hypothesis of their instantaneous impact origin. Mare basins are endogenous structures which, most probably, were formed by tectonic and magmatic processes.

Regularities in the Distribution of Circular Mare Basins and Mare Material on the Moon's Surface /233

Some regularity in the distribution of mare formations on the Moon's surface were examined earlier. The link was described between circular mare with irregularly shaped mare, entering completely or partially into ring or arc peripheral belts. It was noted that a number of irregularly shaped mare basins were confined to large linear zones stretching from the northwest to the southeast. Here the more formal question of the quantitative distribution of circular mare basins and mare formations as a whole by latitudes and longitudes on the Moon's surface is discussed.

The distribution of circular maria, whose boundaries were determined by the large marginal cordillera, do not show obvious regularity (Fig. 8). However, two facts become clear. First, the size of circular maria on the near side, on an average, is greater than on the far side (see Table 2). Second, there is a "preference," hardly noticeable, for circular maria to be in moderate latitudes. With closer analysis, it becomes clear that the axial plane to which most circular mare basins are confined intersects the equator on the boundary of the near and far sides, and on the near side deviates noticeably to the north, and on the far side to the south (Pskovskiy, 1968).

Clearer regularities are shown when analyzing the distribution not only of circular basins, but other formations of mare

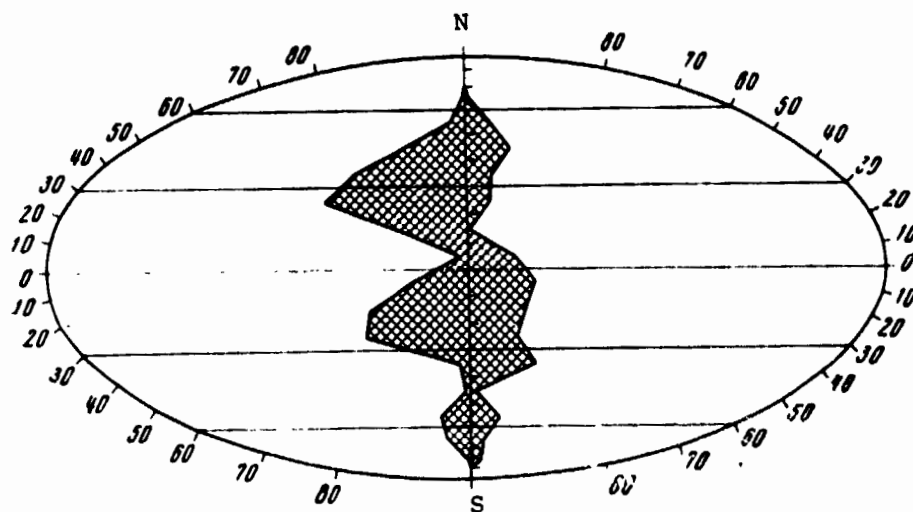


Fig. 8. The distribution of circular mare basins by latitude of the near (left) and far (right) hemispheres of the Moon. Areas occupied by basins are shaded. The grouping interval is 10° .

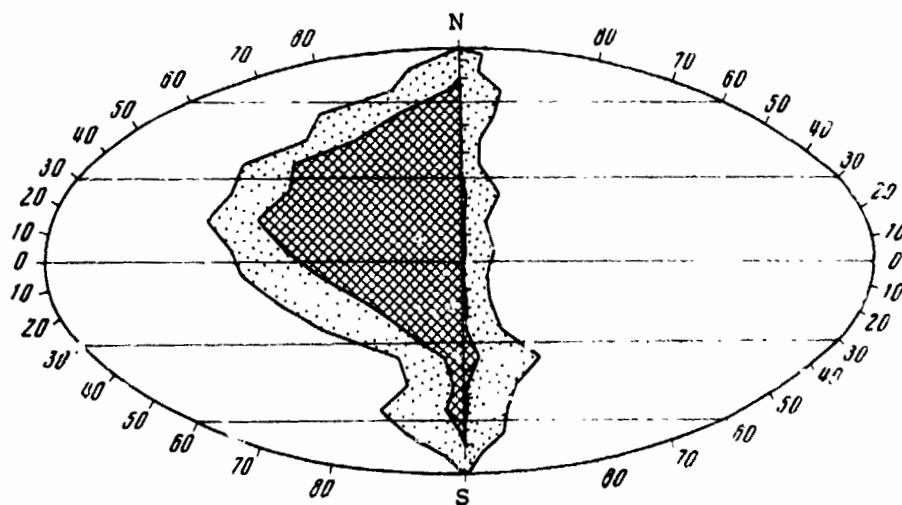


Fig. 9. Distributions of areas occupied by mare material of Procellarum and youngest complexes (shaded), Altaic and Median complexes (dots) along latitudes of the near (left) and far (right) hemispheres of the Moon. The grouping interval is 10° .

material, especially Procellarum and younger formations connected with them (Fig. 9). It appears that the overwhelming majority of areas occupied by the Procellarum complex is on the near side

(Mikhaylov, 1963). Furthermore, of the small amount of Procellarum and younger mare material on the far side, a considerable part is on the region near the limb (Mare Orientale, Mare Smythii, Mare Marginis, and Mare Humboldtianum and structural forms linked with them). There is also a similar regularity for older mare formations (Altaic and Median), but it is more weakly expressed. Part of the Nebular complex, which can be assumed to be of primary mare origin, as it were, do not give "preference" either to the near or far side; however, difficulties in isolating Nebular mare formations make this conclusion particularly hypothetical.

/234

Another regularity is less well expressed: the fact that mare complexes are confined to equatorial and moderate latitudes. This is hardly noticed when analyzing regions of the distribution of old mare formations and is better expressed in the distribution of Procellarum material. Apparently, this regularity, to a great extent, is inherent on the near and not the far side of the Moon.

Probably, only the preferential distribution of circular maria in equatorial latitudes can be explained from the point of view of the impact origin of mare structures (meteorite orbits of the solar system more often pass near the ecliptic plane). But the relative abundance of irregularly shaped maria in equatorial and moderate latitudes and, furthermore, the sharp difference between the far and near sides do not give any convincing explanations. It is particularly difficult to understand from such positions why mare basins on the near side, laid down in the same epoch as those on the far side, continued to develop during the accumulation of the Procellarum complex and later, whereas most basins on the far side stopped developing towards the beginning of the Procellarum stage.

All regularities of their distribution over the surface of the Moon can be explained from the position of endogenous origin. If one considers that lunar maria are the structural expression of magmatic processes within the Moon whose basic energy source was the decay of radioactive isotopes, then the weakly expressed "preference" of maria to equatorial and moderate latitudes can be determined by the small disturbance of the heat balance due to the large heating-up of equatorial latitudes by the Sun (Levin, 1963). The preferential distribution of mare material on the near side can be naturally linked with the tidal influence of the Earth, which was especially effective during the early stages of the system's evolution when the Moon was much nearer to the Earth than it is now. This presupposes that, at least from the time of accumulation of the Altaic mare rock complex (approximately 4 billion years ago), the Moon was a satellite of the Earth, with one side turned towards it -- a consideration which must be taken into account when calculating the tidal evolution of the Earth-Moon system.

/235

Tidal friction could also be an additional source of heating-up, but apparently its basic influence in magmatic activity consisted of something else: tectonic stresses, caused by tidal friction in the body of the Moon, caused deformations and displacements along fractures, causing, by the same token, hypomagma to emerge on the surface. In light of this, the link shown above between mare basins and fractures, possible magmatic channels, is significant.

Magmatism, Mascons and the Lunar Crust

The evidence shown for the endogenous origin of lunar mare basins leads one to the conclusion that there was great tectonic and magmatic activity on the Moon during the early stages of its development. The relationships between various mare rock complexes are best explained if they are looked upon as volcanic formations. All this creates interest in any indications of old magmatic activity in lunar mare basins.

A comparison of lunar relief forms with terrestrial volcanic formations shows the similarity of some forms on the lunar mare surface with the relief of areal volcanism regions (Kuiper et al., 1966; Trifonov, 1969b).

Another direction of research into lunar magmatism is linked with processing and interpreting lunar soil samples. Without repeating here the content of numerous published works, we shall only note that the overwhelming majority of lunar rocks analyzed has a basic composition and gravitates to one of two varieties: basalts with a high iron or alumina content and rocks of the gabbro-anorthosite group. There were also intermediate varieties among samples brought back by Apollo 12, Apollo 14 and Apollo 15.

Basalts with a high iron content, in places with a considerable titanium content, are lunar mare basin formations and relate to the Procellarum complex. Rocks with a high alumina content are characteristic of lunar highlands and are probably linked with magmatic craters and positive volcanic formations (in the future, for brevity we shall call these crater formations). As for pre-Procellarum mare rocks, in most cases it is assumed that they are chemically similar to Procellarum; in some places relatively light mare complexes could be formed by rocks with an increased alumina content. Probably, the differences in chemical composition of the fused rocks determined the nature of magmatic activity and were reflected in the diversity of relief forms created by it. It can be assumed that the differences shown determine the nonuniformity of the lunar crust which is made up of rocks fused from the Moon's primary matter. According to petrologic research and experiments, mare basalts were fused from depths of more than 200 km, and rocks with a high alumina content could be

/236

the result of the differentiation of primary fusion products or fusion products at depths of 150-180 km (Ringwood, Essene, 1970; O'Hara et al., 1970).

P. M. Muller and W. L. Sjogren (1968) published a chart of the gravitational anomalies of much of the Moon's visible hemisphere. The anomalies are shown by analyzing the irregularities of the movement of artificial Moon satellites and were carried out at an altitude of 100 km above its surface. In essence, these are anomalies "in free air," but at such a great altitude almost coincide with isostatic ones. Significant positive anomalies (up to 200 mGal and above), called mascons, have been isolated on a background of relatively weak fluctuations (up to 50 mGal). They coincide with the largest circular maria of the Moon: Imbrium, Claritas, Crisium, Humorum, Nectaris and Orientale. The differences in the gravitational forces of circular maria and the remaining regions of the Moon are commensurate with the largest anomalies on Earth. Later, information appeared which made it possible to assume the presence of a similar anomaly in the region of the circular Mare Smythii and a considerable anomaly in the central part of the far side of the Moon (O'Leary et al., 1968). The latter could be the total effect of several anomalies linked with old circular maria on the far side, but further experiments are needed to check the supposition. W. M. Kaula (1970) doubts the existence of such an anomaly. The obvious link of other anomalies with circular maria determined the nature of suggested interpretations.

The authors of charts and a series of other investigations (Stipe, 1968; Urey, 1968) supposedly link mascons with the intrusion of foreign masses into the Moon's body. In previous chapters of this work, the theory of the impact origin of circular maria was shown to be unsound, which also makes one doubt the suggested interpretation. J. A. O'Keefe (1968) raises objections to this using other arguments.

Explanations of the nature of mascons from a position of their endogenous origin are divided into two groups. Some researchers (O'Keefe, 1968; Kropotkin, 1971) draw attention to the isostatic, even nature of the great part of the lunar surface caused by the existence of a crustal layer varying in thickness, "floating" on a denser substratum. Mascons correspond to regions where dense subcrustal masses are found closer to the surface than below other areas (Markov, Sukhanov, 1970) and probably almost reach it (Kropotkin, 1971), not being leveled isostatically. Probably, under lunar conditions, the crust is represented by basalt rocks fused from primary matter. Accepting their mean density to be 3.1 g/cm^3 , we find that these anomalies could be caused by the increase in thickness by 40-50 km in other regions of the Moon, when there is a thin crust in circular maria. However, it is difficult to coordinate this with the high intensity of volcanism 237

in circular maria which is hardly less than that on the remaining areas.

On the basis of interpretations by other researchers, a difference has been shown in the density of the surface or crustal layer in circular maria and outside of them. J. E. Conel and G. B. Holstrom (1968) and R. Baldwin (1968) suggest that mascons can be viewed as plates or lenses of dense matter on the surface of circular maria, and R. Baldwin sees them as the products of lava effusions into basins, occurring from the impact of large cosmic bodies. According to J. E. Conel and G. B. Holstrom, the thickness of this plate in Mare Claritas should be 14 km when the density margin of mare masses is 1.1 g/cm^3 and 30.8 km when the density margin is 0.54 g/cm^3 .

If the density of the plate coincides with that of the investigated mare rock, it is somewhat lower than the Moon's mean density. Therefore, the mass margins could only be reached using this interpretation by the difference of densities of the crustal layer in circular maria and outside of them. However, crystalline rocks of basic composition which probably make up the lunar crust outside of circular maria could hardly have such a low density, which could give positive, isostatic anomalies of plates according to calculations by J. E. Conel and G. B. Holstrom (2.7 g/cm^3 and, especially, 2.1 g/cm^3). Nor can the different porosity of the crustal material cause this effect since, as J. A. O'Keefe (1968) showed, the porosity of lunar rocks rapidly decreases with depth.

Interesting solutions to this problem were suggested by M. J. O'Hara et al. (1970) and A. E. Ringwood and E. Essene (1970). M. J. O'Hara's solutions is based on the analogy of lunar maria with lava lakes. Assuming the gravitational differentiation of lava, the authors suggest an enriching of the "bottom" material by oxides of iron and titanium, and link mascons of circular maria with this. This model appears unacceptable to us for two reasons. First, the geologic mapping of the Moon shows that lunar maria are filled with rock complexes of different ages, each of which possibly consists of several covers. Therefore, analogies with a lava lake on the large scale necessary to create these mascons are inadmissible, although small lava lakes could have occurred in some places during mare and crater volcanism. Secondly, the suggested enrichment of magma by iron and, especially, titanium leads to a source model for partial fusion which would have an abnormally high density and unique composition for the Moon. Such a composition of primary matter in the Moon's interior cannot be obtained using a suggested hypothesis of its origin on wide scales (and circular maria are distributed sufficiently widely).

When there is a small amount of partial fusion (3%), that is, a small depth of basaltic mare crust, A. E. Ringwood and E. Essene explain mascons as a transition of gabbro-like association

(3.36 g/cm³) into an eclogite one (calculated density 3.74 g/cm³). According to the experimental data of these authors, this transition for lunar mare basalts (reduced content of Na and Si, the high content of Fe) is achieved at much lower pressures than for gabbro-like rocks in the Earth's interior. The transition into eclogite could occur in the base of the crust of circular maria at depths of approximately 50 km (3 kbar) at temperatures of 660-730°C, and in the suggested gabbro-like intrusions below them at depths of up to 100-200 km (5-10 kbar) at 750-1000°C. Only two aspects of this solution cause doubt. First, are the volumes of basalt or gabbro-like rocks large enough at these depths to cause mascons below circular maria? Second, would the position of the curve of gabbro-eclogite transition alter the fact that the reduction of the Na content could be linked with surface outgassing and is not characteristic of deep crystallization products of basalt magmas? /238

These difficulties forced one to turn one's attention to models of the crust with density differences of circular maria and other territories, smaller in size, but taking in larger volumes of rocks. J. A. O'Keefe (1968) indicated the smaller differences in densities as a possible additional source of mascons. These positions have been validated in later works (Phinney et al., 1969; Wood et al., 1970; Trifonov, 1971). Relying on the approximate results of research into the chemical composition of rocks, R. A. Phinney and co-authors determined the mean density of mare material to be 3.17-3.20 g/cm³, and material from lunar elevations to be 2.97 g/cm³. They believe the first to be characteristic of circular lunar maria and the second, characteristic of the remaining areas. These density differences ought to be maintained up to a depth of 50 km to cause mascons. If the density of rocks beneath circular mare basins is close to the mean density of the Moon (3.34 g/cm³), a crust with a thickness of 32 km is sufficient for compensating mascons.

According to J. A. Wood and his co-workers, a gabbro-anorthosite layer with a density of 2.9 g/cm³ "floats" on a basalt layer with a density of 3.3 g/cm³, and the latter appears on the surface in circular maria. The measured value of mascons is attained when the thickness of the gabbro-anorthosite layer is 25 km and when there is an observed difference of altitudes of its surface and that of mare basins on the Moon. The only objection to both models is the fact that not only craters and formations associated with them, the density of which is probably close to gabbro-anorthosites, but mare rock complexes are widespread outside of circular maria; it is possible that there are also exposures of incompletely reworked initial lunar material. The density of this mixture is higher than that of gabbro-anorthosites.

The models of the lunar crust suggested below are based on the following information and suppositions. The Moon's

gravitational anomalies are completely determined by the inhomogeneities of the crustal layer. The densities of these or other types of crust correspond to their densities on the Moon's surface (we have in mind the densities of nonporous rocks or the densities of a skeleton in porous varieties). The densities of basalt rocks at the Apollo 11 landing site are 3.1-3.5 g/cm³ ("Preliminary examination...", 1969). Their calculated density according to A. E. Ringwood and E. Essene (1970) is 3.36 g/cm³. Recalculations based on different chemical compositions allow one to determine the mean density of basalt mare rocks as 3.25 ± 0.5 g/cm³. The densities of fragments of anorthosite rocks in a thin fraction from Apollo 11 are, on an average, 2.87 g/cm³ (Wood et al., 1970). By assuming, according to information of Surveyor 7, Luna 20, Apollo 14 and Apollo 15, that the material of endogenous craters on the Moon, as a whole, contains less anorthosite and more gabbro-anorthosites and anorthosite-gabbros than the fragments mentioned, we shall accept the mean density of crater material as 2.95 ± 0.05 g/cm³.

The simplest calculations on the thickness of the lunar crust are close to those used by J. A. Wood and his co-workers. It is accepted that the lunar crust is mainly isostatically compensated, that is, unevenness of the relief is compensated by density differences. Here, an equality should be maintained $\rho_1 h_1 = \rho_2 h_2$, where h_1 and h_2 are the thicknesses of rock columns where isostatic equalization is realized, and ρ_1 and ρ_2 are their mean densities (Fig. 10). Positive isostatic anomalies in circular maria are arbitrarily thought to be linked with masses of mare rocks in excess of that which is required for compensation. Their depth L can be calculated from the correlation Δg (mGal) = $= 41.9\rho L$ (Wood et al., 1970), where Δg is the value of the isostatic anomaly and ρ is the density of mare rocks to which the anomaly is arbitrarily assigned. In a particular case it can equal the mean density of the rock column, providing isostatic compensation beneath circular maria. Δg is accepted as equalling the arithmetic mean of the maximum values of anomalies of seven round maria (Muller, Sjogren, 1968; O'Leary et al., 1968) -- approximately 200 mGal. /239

The mean distance to the Moon's center where there is a distribution of Procellarum and younger mare rocks is 1.4 km less than

³ In our simplified calculations it is accepted that the crustal boundary of circular maria and other areas is vertical, and the gravitational anomaly is identical beneath the whole area of a circular maria. In fact, a diagram of anomalies is more complex, and they only reach their maximum value beneath the central part of the mare basin. The correlation to this diagram can be reached by matching the shape of a body causing the gravitational anomaly (Wise, 1970), i.e. changing the boundary outlines of the crust of circular maria and adjoining areas.

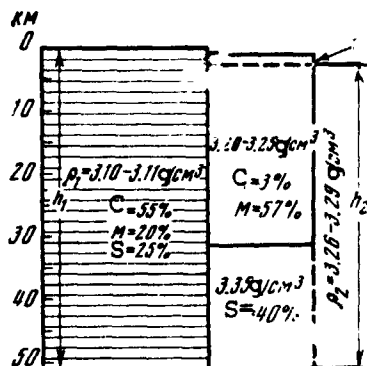


Fig. 10. A diagrammatic model of the lunar crust in circular maria (on the right) and outside of them (on the left). C - crater material, M - mare material, S - substratum which has not been reworked. The remaining explanations are shown in the text.

in craters and old mare regions (Gavrilov, 1969). Since circular mare basins with anomalous values of increase of gravitational force only occupy areas of the first type, the mean excess of the lunar surface outside of circular maria over circular maria is only 1.2 km. In this case, equality $h_1 = h_2 + L + 1.2$ km takes place (see Fig. 10). The formulas shown allow one to determine the possible thicknesses of the lunar crust with these or other ratios of rocks of different density in the crust of circular maria and outside of them, according to the formula $h_1 = (L + 1.2) \times \rho_2 / (\rho_2 - \rho_1)$.

In the simplest case, it can be accepted that the lower boundary of the crust in circular maria and outside of them passes on one hypsometric level, that the ratios of crater and mare material in the crust are similar to the ratios in the surface layer, which can be studied by geological interpretation methods, and, finally, that all large craters are made of rocks of the gabbro-anorthosite type, that is, are magmatic formations. Light, large craters and rare accumulative elevations on the surface of circular maria

are related to a few exceptions to the Eratosthenian and Copernican complexes and occupy areas of not more than 5%. Therefore, the mean density of rocks of the crust of circular maria as a value of 3.20-3.25 g/cm³.

Crater and mare formations are seen with varying frequency outside of circular maria. In irregularly shaped maria, where the surface layer is made up of Procellarum and younger mare rocks, large craters of the Eratosthenian and Copernican complexes are no more widely distributed than in circular maria. However, old crater formations, the relicts of which are exposed above the mare surface, are more widely distributed. There are significantly more large craters of various age in development regions of the Nebular complex. In places they occupy more than 60% of the surface. For areas outside of circular maria, it can be accepted, on an average, that mare and crater formations occupy almost identical areas, and up to 10% of the surface includes exposures of a peridotitic base with a density of approximately 3.35 g/cm³. The mean density of the crust outside of circular maria equals 3.10-3.12 g/cm³, and the thickness of the crust is 70-86 km.

/240

With this crustal volume, the low-melting phase of which it is composed is 10-12% of the Moon's primary matter. A. P. Vinogradov (1961) assumes fusion to be no more than 14% of the liquid phase in the "zone melting" of chondritic matter. Consequently, the model obtained is possible in principle. However, it is more probable that not the whole volume of primary matter was fused, and the degree of partial fusion was lower. The latter agrees with the increased concentrations of some rare elements in lunar mare rocks. Therefore, preference should be given to the model of the crust with a smaller thickness.

In the models examined, all large craters are thought to be made up of gabbro-anorthosite rocks and types similar to them. However, it is more probable that many impact-meteorite craters are a mixture of material of magmatic craters and mare rocks, that is the amount of purely crater material in crater regions is less than that which is accepted for calculations, and the thickness of the crust is correspondingly greater. Another factor which could effect the estimation of density characteristics of the lunar crust is the transition of mare-type gabbros or basalts into eclogite. According to information by A. E. Ringwood and E. Essene (1970), this transition could have taken place at depths greater than 50 km. For gabbro-anorthosites and anorthosite-gabbros, a transition such as this could only be done at significantly larger depths and, therefore, on the Moon this is probably not seen. If 10% of mare rocks of the crust model described become eclogite with a density of 3.7 g/cm^3 , the mean thickness of the crust is 60-70 km.

There are two more facts, linked with the suggested features of the distribution of products of lunar magmatic activity, which can change the calculated thickness of the lunar crust. It is extremely probable that the intensive segregation of undifferentiated basalt magmas taking place in circular maria from depths greater than 200 km caused a significant heat loss, and this limited the possibility of transforming initial and fusing new magmas at shallower depths, that is, the possibility for generating crater material. Outside of circular maria, where the emergence of undifferentiated deep magmas on the surface, probably was limited, there was a more complex fusion and fractionation of magmas at intermediate depths. To sum up, when there is a smaller amount of mare type magmas emerging on the surface, the overall amount of the low-melting phase could be larger than in circular maria, mainly due to crater type magmas. The latter only partly emerged on the surface, and partly, and probably in most cases, caused intrusions. Therefore, it can be assumed that the content of crater material increases in low horizons of the crust. The amount of primary matter which has not been reworked probably also increases in this direction.

/241

In the model, allowing for these circumstances, the thickness of the crust in circular maria should be less than outside of them.

It is suggested that a column of rock, compensating the crust of adjoining regions beneath circular maria and, furthermore, creating positive gravitational anomalies, consists of 60% mare rock (with an admixture of 5% crater) and 40% "peridotitic" substratum underlying them. Outside of circular maria, the crust consists of 55% crater, 20% mare and 25% "peridotitic" material which has not been reworked. Here, ρ_1 has a value of 3.10-3.11 g/cm³, and ρ_2 equals 3.26-3.29 g/cm³. The thickness of the crust in circular maria equals 29-32 km, and, outside of them, it is 50-55 km. The low-melting phase making up the crust makes up 6-7% of the Moon's primary matter.

Of course, the last model is especially hypothetical and agrees in the best possible way with geologic, geochemical and geophysical information available. In this model, the mean density of subcrustal masses of the Moon is 3.36 g/cm³, and when reduced to temperature and pressure conditions on the Earth's surface reaches 3.42 g/cm³.

Conclusions

The formation of the structure of mare basins on the Moon --- their warping, the formation of cordilleras and the formation of fault systems -- occurred side by side with the filling of basins by mare rock complexes. Since the last process was geologically prolonged, covering tens and hundreds of millions of years, the formation of the basins themselves took just as long. This is the most important argument against the impact origin of mare basins, making it possible to link their occurrence and development with endogenous, tectonic factors, probably determined by deep magmatic processes. The morphology of the mare surface gives basis to assume, and the structure and composition of mare rocks show, that these processes were manifested in the form of volcanism, very similar to plateau basalt volcanism on Earth. Facts and arguments shown in this work allow one to note in general details the following picture of the formation of mare basins on the Moon during the course of magmatic activity.

The gradual, radioactive heating-up together with other sources of heat in a Moon accumulated from cold particles and fragments led to the fact that approximately 4.6-4.5 billion years ago conditions were created for the partial melting of its interior at depths of approximately 400 km. Somewhat later, these conditions were extended to greater and smaller depths. Owing to the partial fusion of the Moon's interior at depths greater than 200 km, basalt magmas were segregated according to a number of indications similar to "primitive" magmas on Earth: olivine-theolite, alkali-olivine-basalt and picrite. A higher ratio of Fe/(Mg + Fe) in the fusion source was suggested in comparison with regions of generation of young basalt magmas caused a significant enrichment of lunar magma by iron.

Generated magma could arrive on the surface along fracture zones and particularly in the intersection areas of different direction zones. The most complex and frequent intersection is now seen close to circular mare basins. Apparently, it is here that the most satisfactory conditions for the lifting of magma were created. When there is relative "equivalence" of disturbances in different directions and a material heterogeneity of the Moon's interior, these deep magmatic reservoirs acquired outlines which were almost circular, and this led to the circular shape of the area of magmatic effusions on the surface. Magma also rose along large zones of unidirectional faults and arced disturbances around circular maria; however, the volume of effused products here was probably less. The elements of anisotropy, created by the unidirectional nature of disturbances, caused the irregular outlines of the majority of these volcanic regions differing from circular ones.

The orientation of fault disturbances on the Moon is subordinate to the overall planetary regularity in the sense that the preferential directions of faults and fissures belonging to one of the three planetary directions is seen everywhere: the northwest and somewhat less developed northwest and submeridional. Apparently, this fact excludes the possibility that most faults were caused by the impact of meteorites or larger cosmic bodies. The irregular density of faults and the occurrence of particularly intense disturbance zones is linked with other reasons, still not completely understood.

In those cases when magmas reached depths of 150-180 km (or were formed at these depths), but could not rise any higher due to the absence or inefficiency of the conducting channels, crystallization differentiation took place, as a result of which the liquid phase was enriched with alumina. Further fractionation of magmas with a high alumina content could cause the formation of large volumes of rock of the gabbro-anorthosite type and others, significantly rich in plagioclase. Possibly, this type of magmatic activity, linked with intermediate foci, was expressed on the surface in the form of craters⁴ and accumulative elevations. Possibly, relatively acidic differentiation products will also be found in the composition of these complexes.

Geologic mapping of the Moon shows that the formation of craters and development of maria occurred side by side over a long time, but the first process also continued sufficiently intensively after the second had ended or occurred on extremely limited scale. Fusion products probably continued to arrive from depths of less than 200 km after the whole low-melting phase at great depths, which could be separated, had already been separated,

⁴ We have in mind magmatic craters side by side with which, apparently, are impact and meteorite ones.

or could not reach the surface in its changed tectonic conditions without fractionation at intermediate and shallow depths.

Two types of magmatic activity, mare and crater-highland, caused the isolation of the low-melting phase, creating the lunar crust. Apparently, the ratio of formations of different ages with these two types in it is different in various parts of the Moon. The Altaic, Median and, especially, Procellarum rock complexes are confined, to a great extent, to the near rather than the far side of the Moon, and show less clearly the expressed preferential distribution in equatorial and moderate latitudes. It is natural to assume that the differences between the near and far hemispheres are linked with the Earth's tidal influence, which is especially effective when the Moon is sufficiently near it. If this is so, the Moon was fixed with one face towards the Earth not later than 4 billion years ago.

/243

The stability of a fault system laid down in antiquity determined the length and inherited nature of mare volcanism. The result of it was the enrichment of the crust of mare basins by relatively dense magmatic rocks, that is, the occurrence in maria of crustal masses, excessive in comparison with regions of intensive crater magmatism. In this connection, one is drawn to the fact that the outbreaks of the succeeding parts of mare magma apparently led to sinking of sections made up of igneous materials belonging to adjacent territories made up of older formations outside of craters. This feature of lunar mare volcanism was manifested both on the scale of individual exposures of one or another mare rock complex and on the scale of large regions of mare volcanism: they are all expressed in the relief by basins, the surface of which is more than 1 km lower than that of the margins. Probably, this sinking reflects the isostatic leveling of regions with different densities of fused magmatic products.

The fact that the development of mare basins took place over a long time and side by side with volcanic activity assumes the repeated renewal of isostatic leveling processes, which, most probably, could have taken place between epochs of intensive effusions. In irregularly shaped maria, where the overall volume of magmatic mare rocks is relatively small, isostatic leveling was completely or almost completely attained. In circular maria which developed over an especially long period, where the volumes of effused products of mare magmatism were considerably greater, complete leveling did not take place, and excess masses are retained to this day.

Probably, isostatic leveling of mare basins was accompanied by multiple roof subsidence of emptied magmatic reservoirs. The formation of cordillera scarps, arced fissures beyond them and on the margins of maria is linked with the submersion of mare

magmatism regions, particularly intensive in circular maria. Fault-separation movements along these fissures led to the occurrence of peripheral belt basins. These fissures could serve as conducting channels for mare type magmas when they reached the supplying magma reservoir.

A considerable heat transfer during the epoch of intensive volcanism and the decay of radioactive isotopes initiated the congealing of the Moon and the gradual reduction of volcanic activity. Its most expressed manifestation ended recently, probably, no less than 2 billion years ago, but residual processes probably continue to this day. Temporary changes of brightness, color and visibility of lunar objects can be linked with this (Middlehurt, 1966; Middlehurst et al., 1968), most probably confined to relatively young formations: craters, parts of the mare surface, fissures, accumulative elevations in craters and outside them. The increased number of positive temperature anomalies on relatively young mare surfaces also supports this assumption (Markov, Sukhanov, 1969).

/244

Thus, on the Moon, as on Earth, a basalt crust occurred, fused from the planet's interior. Furthermore, on Earth a continental "granite" crust, enriched with magmatic and metamorphic rocks of acidic and intermediate composition was formed and, apparently, still continues to grow. The development of the granite crust at least from later and, possibly, earlier Proterozoic, is linked with a spatially localized geosynclinal process. In earlier epochs, the formation of a granite layer could not be so localized (granite domes). On the Moon there is no structural expression of the geosynclinal process. The fact that on the Moon there are no significant manifestations of acidic or intermediate magmatism (the formations of acidic composition there are most probably residual products of crystallization of basalt magmas) allows one to assume the absence of a "granite" layer in the lunar crust. The stratification of the lunar crust, which is less in comparison with that of the Earth, probably corresponds to the lesser degree of stratification of subcrustal masses. The degree of differentiation of matter on the planet on chemically different horizons is, in this connection, a function of its size and mass.

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